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Renewable Energy-Driven Desalination Hybrids for Sustainability

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Abstract

The expansion trend of current desalination processes is expected to boost brine rejection to 240 km³ and CO₂ emission to 400 million tons per year by 2050. This high brine rejection and CO₂ emission rates are copping COP21 goal, maintaining temperature rise below 2°C. An innovative and energy-efficient process/material is required to achieve Paris Agreement targets. Highly efficient adsorbent cycle integration is proposed with well-proven conventional desalination processes to improve energy efficiency and to reduce environmental and marine pollution. The adsorbent cycle is operated with solar or low-grade industrial waste heat, available in abundance in water stress regions. The proposed integration with membrane processes will save 99% energy and over 150% chemical rejection to sea. In case of thermally driven cycles, the proposed hybridization will improve energy efficiency to 39% and will reduce over 80% chemical rejection. This can be one solution to achieve Paris Agreement (COP21) targets for climate control that can be implemented in near future.

Keywords: desalination, hybridization, sustainability, economics, environmental impact

1. Introduction

The inevitable escalation in economic development has serious implications for environment as energy generation and food-processing processes are vicious to the ecosystem. Energy is extremely important for any economy to generate wealth and the key component for GDP growth. A quadruple growth in energy demand is predicted by The International Energy Outlook 2016 (IEO2016) from 2012 to 2040. It is estimated to grow from 549 quadrillion

British thermal units (Btu) in 2012 to 815 quadrillion Btu in 2040, 48% increase in 28 years. The energy demand could have more than doubled without efficiency gain and suitable energy mix. The non-Organization for Economic Cooperation and Development (non-OECD) countries are the major contributor in this drastic energy demand. In these countries, energy demand rises by 71% from 2012 to 2040 in contrast with only 18% in developed countries in same time span as shown in **Figure 1**. An average GDP growth of 4.2% per year is estimated between 2012 and 2040 in non-OECD countries as compared to 2.0% per year in OECD countries as estimated by IEO2016. In terms of energy consumption by sectors, industry is leading followed by residential and transport. This trend persists from 1971 to 2014, but overall consumption doubled during this period. Power plant sectors consume 35% of global energy, and it is estimated to grow due to urbanization in developing countries. Global electricity demand is expected to increase over 65% from 2014 to 2040, 2.5 times faster than overall energy demand [1–7].

Even though there is a competition between countries for development, but it has severe impact on environment in terms of CO₂ emission. Every drop of fuel pollutes environment and intensity depends on process efficiency. Global CO₂ emission measured as 40 gigaton (Gt) per year in 2016 is almost double as compared to 1980 emission level. Energy sector are the major contributor, 68%, in CO₂ emission and power generation sector sharing 42% in energy sector emission followed by transport 23% and industry 19%. A systematic diversification of the global energy mix and technology improvement driven by economics and climate policies almost flattens the CO₂ emission rate in 2014, only 0.8% increase, as compared to 1.7% in 2013 and 3.5% in 2000. In the past 3 years, 2012–2014, the moderate increase in CO₂ emission, 0.8–1.7%, is

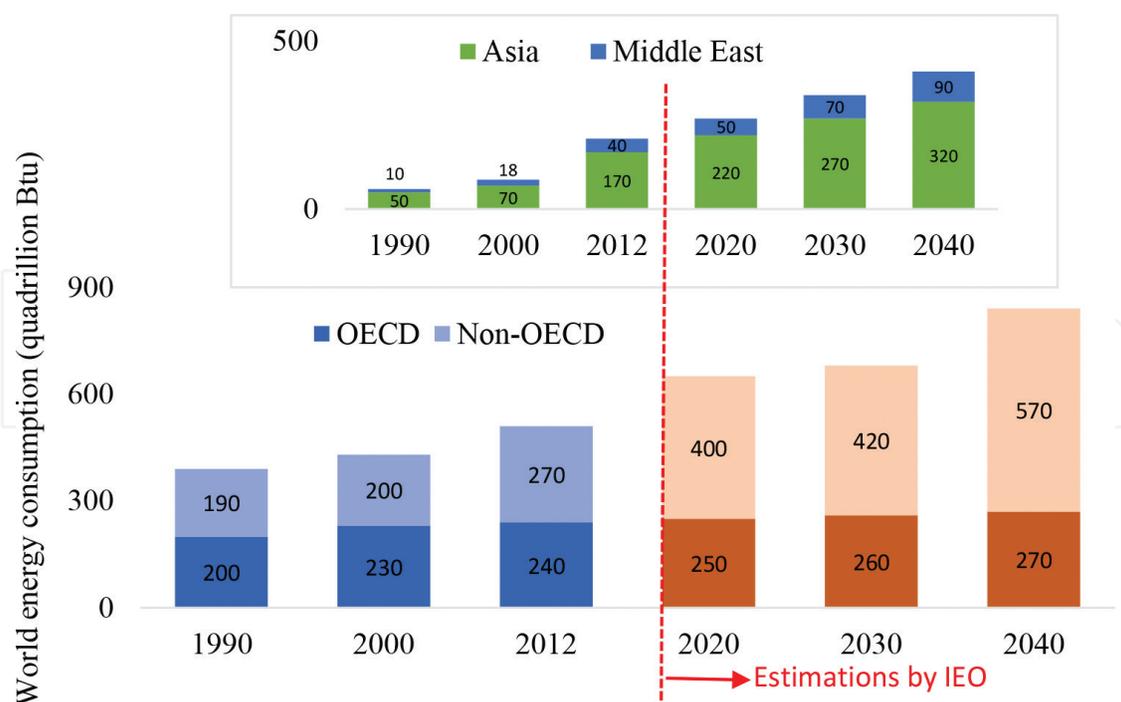


Figure 1. Organization for Economic Cooperation and Development (OECD) and non-OECD countries' energy consumption from 1990 to 2040. Asia and Middle East region show major share in the world energy consumption. IEO2016 estimated the trend from 2017 to 2040 with BAU process [1].

remarkable when global economic growth rate was 3% as compared to 4% emission annually with GDP growth rate of 4.5% in last decade. In other words, partial decoupling of economic growth and CO₂ emission has been observed in last 3 years due to shift in energy production and consumption, power generation, technological improvements and policy implementation. In 2015, the milestone year, 170 countries signed an agreement at the 21st Conference of the Parties (COP21) in Paris for climate action. The Paris Agreement is the first international climate agreement extending mitigation obligations to all developed and developing countries representing over 90% of energy-related CO₂ emissions and approximately 7 billion people. The agreement aim to achieve CO₂ emission peak as soon as possible to cap the increase in the global average temperature to below 2°C. In addition, it also aims to pursue extra efforts to limit the temperature increase to 1.5°C. Business as usual (BAU) scenario, as most of the countries followed, can lead to over 5°C temperature increase as shown in **Figure 2** [8–25].

In Middle East, fast economic growth along with structural changes is expected to increase energy consumption to over 90% (30 quadrillion Btu) from 2012 to 2040. In GCC countries, the electricity demand has been increased at thrice the global average over the last few years due to many factors such as (i) high economic growth rate, (ii) huge development projects encouraging policies, (iii) government subsidies and (iv) higher cooling and water demand. The United Nations Environment Program identified the GCC countries as the highest per capita energy consumption in the world and they contribute 45–50% cumulative Arab countries' CO₂ emissions. Saudi Arabia is leading in power generation as well as in CO₂ emission in GCC countries followed by UAE, Kuwait, Qatar, Oman and Bahrain as shown in **Figure 3**. Increasing energy demand and CO₂ emission inspired the regional government to improve energy efficiency, diversifying energy mix and to devise strategies for alternative renewable energy sources to conserve natural resources and environment [26–37].

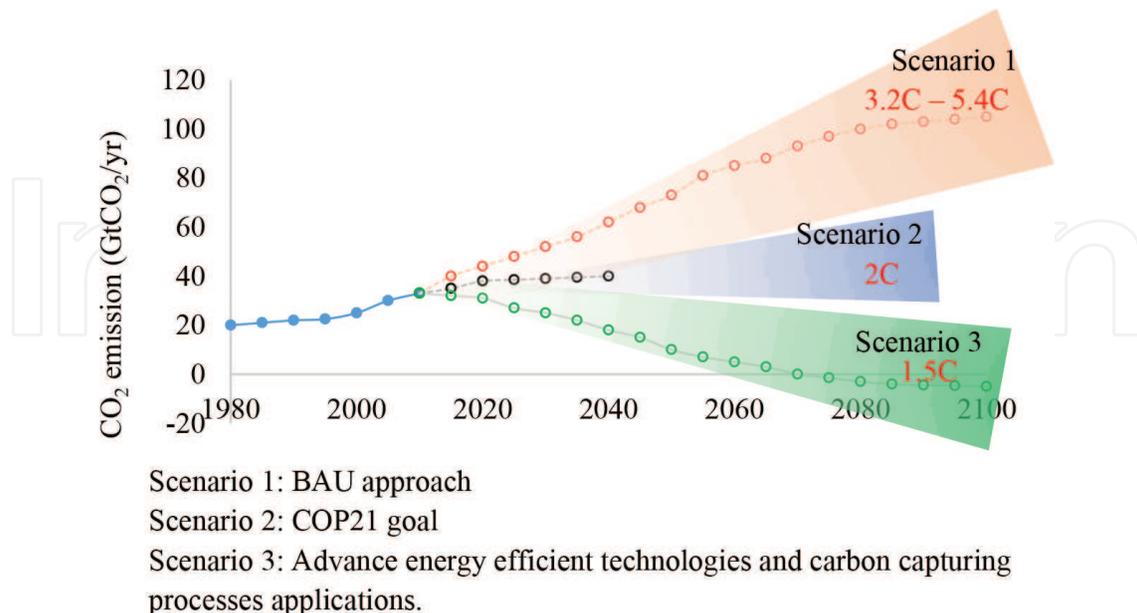


Figure 2. CO₂ emission trends impact on environmental at three different scenarios: (i) business as usual approach will lead to 3–6°C ambient temperature increase, (ii) COP21 goal targets to control emission to maintain temperature increase below 2°C and (iii) advance processes/technologies to lower temperature increase to 1.5°C [8, 9].

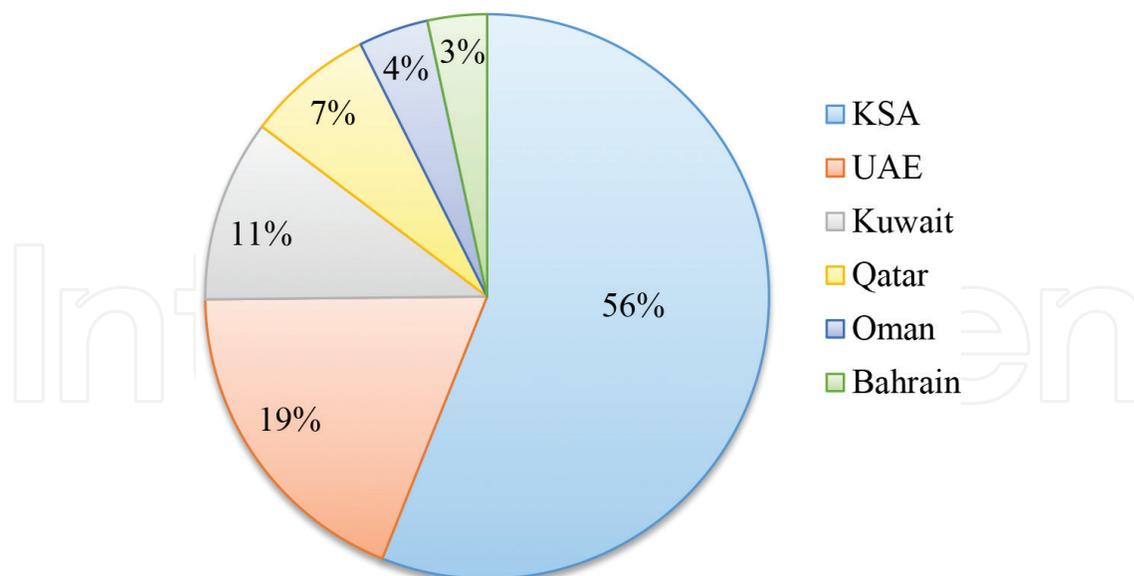


Figure 3. CO₂ emissions trends in Gulf Cooperation Council (GCC) countries. Saudi Arabia is leading with 56% emission due to high electricity and water demand and poor energy-efficient process applications [5].

1.1. Energy efficiency and renewable energy targets for electricity generation

GCC countries already planned energy efficiency and renewable energy targets for 2030 as shown in **Figure 4**. As a global sunbelt region, solar energy has received particular attention due to abundance availability in the region and falling cost of technology, particularly photovoltaic (PV). Renewable energy plans of GCC will result in cumulative 2.5 Billion barrels of oil equivalent saving from 2015 to 2030 equivalent to USD 55–87 billion savings. Implementation of renewable energy sources and decrease of fossil fuel consumption will reduce a cumulative total of 1 gigaton (Gt) of CO₂ emission by 2030. This will result in 8% reduction in the region's per capita carbon footprint, in line with the countries' Intended Nationally Determined Contributions (INDC) submissions to the Paris climate conference (COP21). In addition to CO₂ savings, energy efficiency and renewable energy application will reduce 16% of water consumption in power generation sector. This will save 11 trillion liters of water per year that will not only have ecological benefits but will also reduce energy consumption for water desalination [38–47].

In GCC region, energy intensive desalination processes are the major contributor to satisfy the increasing water demand with the development of infrastructure. The regional water demand is expected to increase to fivefold by 2050. The water is utilized during fossil fuel extraction, industrial processing, domestic purposes, cooling and power generation. The analyst predicted that the scale of water utilized for energy production only will increase from 583 billion cubic meters (bcm) in 2010 to 790 bcm of water in 2013, resulting in even higher demand for desalination in the region [47]. Desalination technologies development and alternate energy mix are required urgently to coup the BAU trend.

1.2. Energy efficiency and renewable application for desalination

Currently, GCC countries' cumulative desalination capacity is 26 million cubic meter (mcm) per day, equivalent to 36% of total global capacity. GCC countries are set to ramp up their desalination infrastructure 6–10% annually till 2040, extending total capacity to almost twofold. These

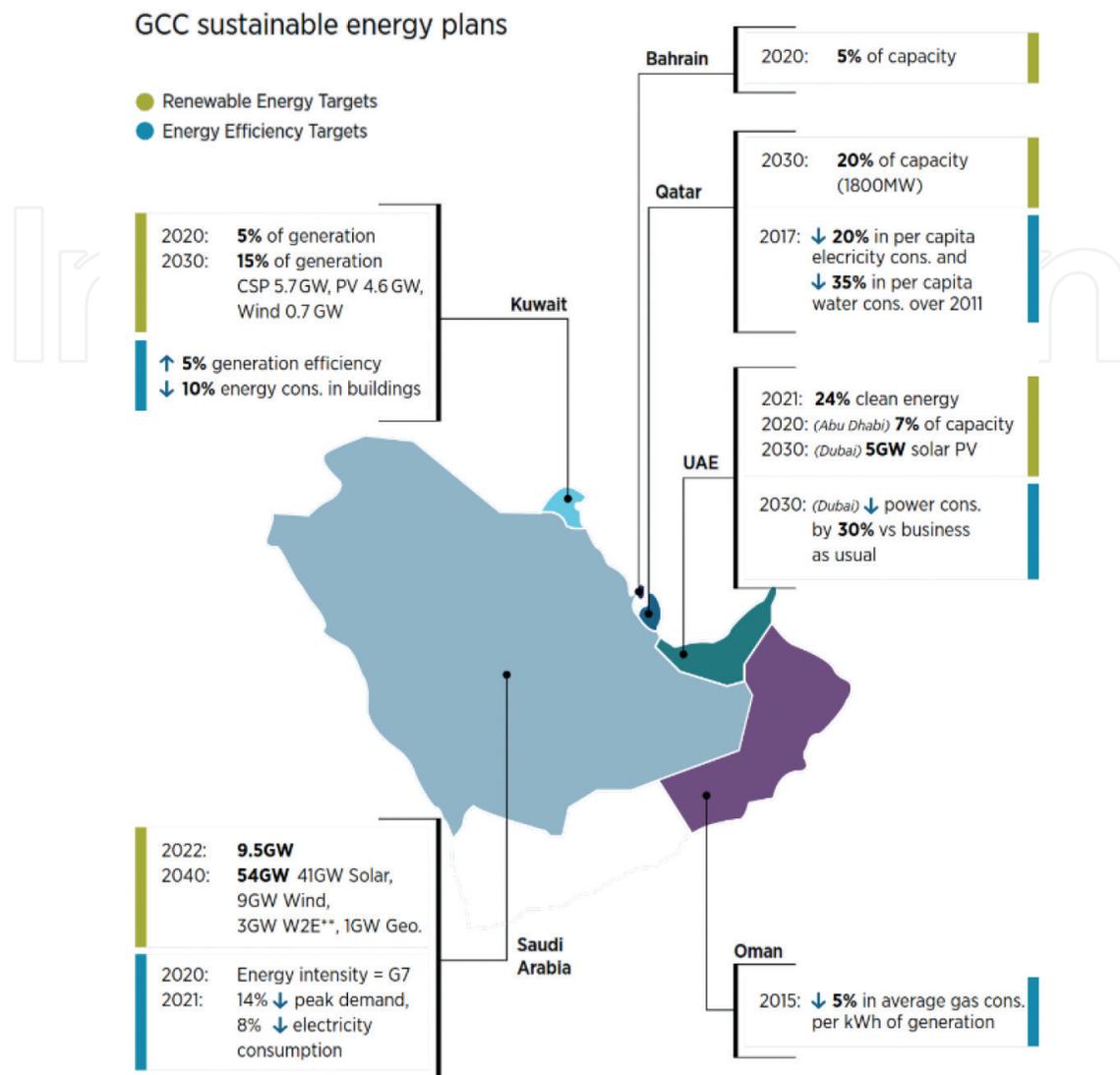


Figure 4. Gulf Cooperation Council (GCC) countries' targets for renewable energy applications and processes energy efficiency. Saudi Arabia planned to inject 54 GW electricity from renewable sources by 2040 [6].

beyond limit extensions of fossil fuel operated desalination capacities will have significant impact on regional economy. For example, Saudi Arabia consuming nearly 300,000 barrels of oil for thermal desalination to fulfill daily water demand and similar challenges are faced by other GCC countries. Traditionally, in GCC region, thermal desalination processes (MSF & MED) are preferred over membrane-based (SWRO) processes due to two main reasons: (i) extensive pre-treatment requirement for SWRO processes due to high salinity in Arabian Gulf and (ii) energy efficiency of thermally driven processes by utilizing residual low grade heat due to integrated water-and-power projects.

Thermal desalination processes gained confidence by operating for over 30 years in GCC region, and they are well integrated into power generation infrastructure. In terms of sea areas, Arabian Gulf is the largest intake facility for desalination capacities and producing 12.1 mcm per day. United Arab Emirates is dominating with 23% desalination capacity in Gulf followed by Saudi Arabia 11% and Kuwait 6%. In the Red Sea area, desalination plants have a total production capacity of 3.6 mcm per day, dominating by co-generation plants (72%).

Saudi Arabia accounts for 92% of the desalinated capacities in the Red Sea region, thermal desalination dominating by 78% installations (2.6 mcm per day). Major desalination installations in Red Sea, their size and technology type are presented in **Figure 5** [48–56].

In addition to less energy efficient, conventional desalination processes have enormous impact on marine line and environmental in terms of volume of brine rejection and CO₂ emissions. It is estimated that the brine rejection will increase to 240 km³ and emission will be approximately

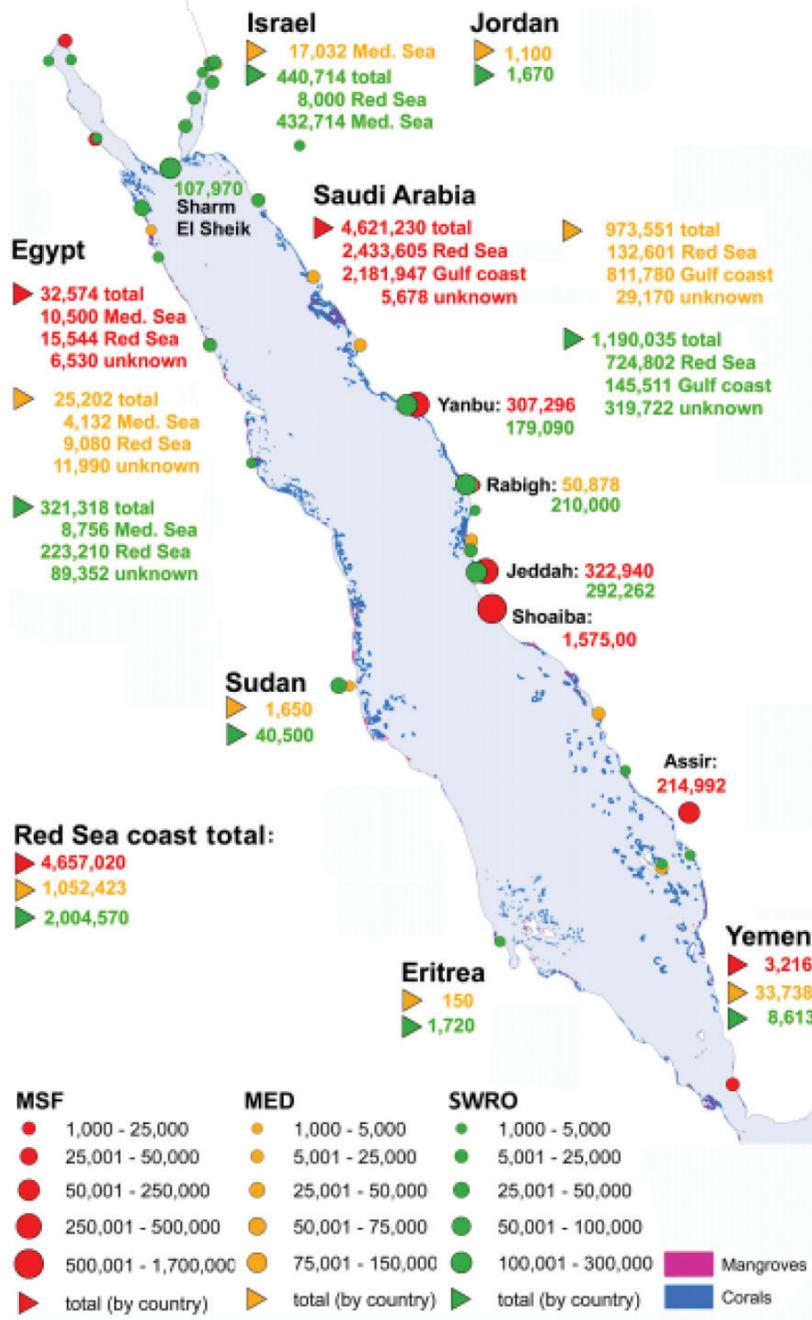


Figure 5. Location and size of major thermal- and membrane-based desalination installations along Red Sea, Gulf Coast and Mediterranean Sea. Thermal desalination processes are dominating due to severe feedwater conditions in GCC countries [56].

		Impact		
Probability		1	2	3
	1			
	2			
	3			
			SWRO (I × P)	Thermal (I × P)
Energy			3 × 3	3 × 3
CO ₂ emission			3 × 3	3 × 2
Chemical rejection			3 × 3	3 × 2
Brine concentration			3 × 2	3 × 1
Brine temperature			1 × 1	1 × 1
Pumps noise			3 × 2	2 × 1
			Low impact	
			Moderate	
			High impact	
			Severe impact	

Table 1. The impact matrix of conventional desalination processes. Both processes showed severe impact in terms of energy consumption, chemical rejection and CO₂ emission. Impact of SWRO processes is worse than thermal processes.

400 million tons of carbon equivalents per year by 2050. In the Gulf, 23.7 metric tons (mt) of chlorine, 64.9 mt of antiscalants and 296 kg of copper rejection are estimated from desalination installations, and in Red Sea, these rejections are 5.6 mt of chlorine, 20.7 mt of antiscalants and 74 kg of copper [57–61]. The impact of conventional desalination processes on energy and environment can be judged by the developed risk matrix as shown in **Table 1**. It can be seen that SWRO processes are operating in severe impact zone (half elements are in the red zone) while thermal desalination processes are higher than moderate zone (two elements are in the red zone).

Therefore, energy-efficient desalination processes (innovative hybrid cycles) and transitioning towards alternate renewable energies are two key innovation pillars needed to address future sustainable desalination water supplies in the region.

Hybrid desalination projects (SWRO/MSF, MSF/MED), for energy efficiency, were proposed and implemented to few facilities such as Jeddah-II, Fujairah II and Ras AL-Khair in the past [62–88]. Unfortunately, hybrid concept was unable to get much industrial implementation due to operational limitations. Today, industrial scale desalination processes pairing with innovative cycles are well needed to pave the way for future desalination in GCC under COP21 goal. We proposed an innovative adsorption (AD) cycle hybridization with SWRO and MED to meet COP21 accord. The proposed AD cycle utilized low-grade waste heat or renewable energy such as solar or geothermal to produce fresh water. The integration of AD

cycle with conventional desalination processes will help to overcome their operational limitations. For example, in first case, RO + AD integration can boost overall recovery to over 80% as compared to 35–40% of RO alone. This will help to protect marine pollution by reducing pretreatment chemical rejection into the sea. In second case, its hybridization with thermal processes such as MED + AD will help to overcome last stage operational temperature limitations of conventional MED system by extending to as low as 7°C as compared to 40°C in conventional processes. It will help to boost water production to almost twofold with same energy input. In both cases, CO₂ emission will reduce as AD cycle utilized only low-grade industrial waste heat or renewable energy. We presented detailed experimentation of both mentioned cases and their economic analysis to show the superiority of hybrid cycles over conventional processes in terms of energy efficiency, marine and environmental impact.

2. The basic adsorbent cycle

The basic adsorbent cycle consists of four major components, namely (i) evaporator, (ii) adsorbent beds, (iii) condenser and (iv) circulation pumps as shown in **Figure 6**. The feedwater is supplied to evaporator and saturation pressure is maintained by the adsorbent uptake capacity to achieve evaporation conditions below ambient level. Once the adsorbent bed is near saturation, adsorption process switched to second bed and regeneration heat is supplied to desorb vapor and prepare adsorbent for next cycle adsorption. The desorbed vapor is condensed in the condenser by circulating the chilled water from evaporator. It can be noticed that electricity

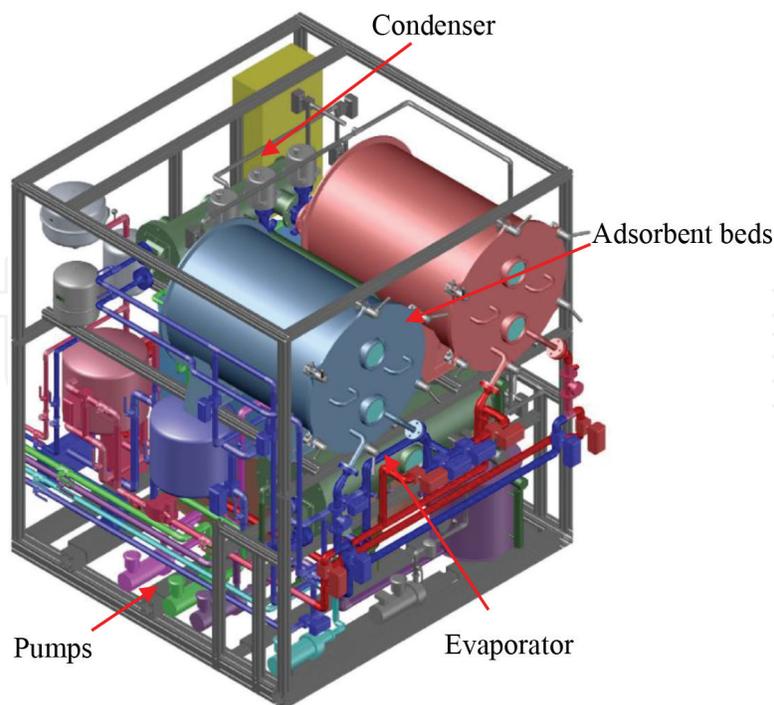


Figure 6. Adsorbent cycle 3D model can operate with solar or industrial waste heat from 55 to 85°C. The adsorbent is packed in the beds.

Adsorbent	Cost	Application status
Silica gel	Low	Industrial scale
Metal organic framework (MOF)	High	Research based only
Zeolite	High	Medium pilot

Table 2. Summary of major adsorbent, their cost and technological application status. Silica gel is most applied adsorbent because of its stability and reliability [110].

is only supplied for pumping of liquid and major thermal energy is supplied from renewable solar or industrial process waste heat from 55–85°C. The detail of adsorption cycle can be found in published literature [89–105]. The adsorbent selection depends on application temperature. The list of most common adsorbent and their application status are provided in **Table 2**. We developed an advance silica gel with improved uptake by pore opening. We also developed silica gel-coated heat exchanger AD cycle that can achieve heat transfer coefficient twofold higher as compared to conventional packed bed AD cycle [106, 107]. Silica gel has many advantages such as (i) easily available, (ii) lower cost as compared to all available adsorbent, (iii) more stable and reliable and (iv) easy to modify for required application [108–111].

The proposed adsorbent cycle has capability to integrate with conventional desalination process to improve their performance. The detail of integration with SWRO and thermal processes and their advantages are discussed in the following sections.

3. Membrane process and their integration: energy and environmental impact

In GCC countries, 42% desalinated water is produced by membrane processes. Conventional SWRO processes consume 7–17 kWh_{pe}/m³ primary energy (equivalent to 3–8 kWh_{elec}/m³) for seawater desalination and they emit 3.0 kg/m³ CO₂ to the environment [112]. Currently, major online SWRO plants in Saudi Arabia and future proposed projects is presented in **Table 3**.

Most of the SWRO plants are operated under saline water conversion cooperation (SWCC), and their overall recovery varies from 17 to 40% depending upon feedwater quality. Four major plants, namely (i) Jeddah, (ii) Rbigh, (iii) Jubail and (iv) Shuqaiq operational data were collected, and analysis results are presented.

3.1. SWRO and hybrid cycle results and discussion

Figure 7(a–c) shows the seawater, retentate and distillate concentration for four mentioned plants. It can be seen that Red seawater feed concentration varies from 37,000 ppm in Jeddah to 40,000 ppm in Jubail. The retentate maximum concentration was observed at Jeddah, 60000 ppm due to better recovery. The distillate concentration met the WHO standard, <500 ppm, except at Rbigh where it can reach to 800 pm and it mixed with thermal-driven processes distillate before distribution to end users.

Plant name	Capacity (m ³ /day)	Overall recovery (%)	Commissioning	Operator	Ref
Jeddah phase-II	48,848	35	1994	SWCC	[113]
Rabigh	168,000	40	2009	RAWEC	[114]
Shuqaiq-II	212,000	40	2010	NOMAC	[115]
Ras Azzour	307,000	40	2014	SWCC	[116]
Shuaiba I & II	76,800	40	2003	SEPCO	[117]
Shuaiba III Extension,	150,000	40	2009	SEPCO	[118]
Medina-Yanbu Phase II	127,825	35	1995	SWCC	[119]
North Obhor, Jeddah	12,500	35	2006	SAWACO	[120]
Jeddah-1	56,800	35	1989	SWCC	[121]
Umm Lujj	4400	24	1986	SWCC	
Haql	4400	30	1989	SWCC	
Duba	4400	31	1989	SWCC	
Al-Barik	2275	17	1983	SWCC	
Barge Raka,	24,981			SWCC	[118]
Future projects					
Jeddah phase (4)	400,000		2019	SWCC	[122]
Rabigh phase (3)	600,000		2019		
Alugair	10,000		2019		
Omluj	18,000		2020		
Yanbu-4	450,000		2020		
Jubail phase (3)	330,000		2021		

Table 3. Major SWRO plants in operation and future proposed projects in Saudi Arabia. They need extensive pretreatment and still recovery is only up to 40% maximum.

At these four locations, we also analyzed the CO₂ emission and chemical rejection in the brine and applied to overall capacity in GCC according to SWRO market share. **Table 4** shows the CO₂ emission and chemical rejection per day in the GCC region by SWRO processes only.

The alarming situation, huge amount of CO₂ emission to environment and chemical rejection to sea on daily basis can be clearly observed by conventional SWRO process operation. These processes cannot be terminated due to water requirement, but they can be improved.

Impact of SWRO processes can be minimized either by material development or process improvements. The variety of efficient materials have been proposed such as (i) catalytic nanoparticle-coated ceramic membranes, (ii) zeolitic, (iii) inorganic-organic hybrid nanocomposite membranes and (iv) bio-inspired membranes that includes protein-polymer hybrid

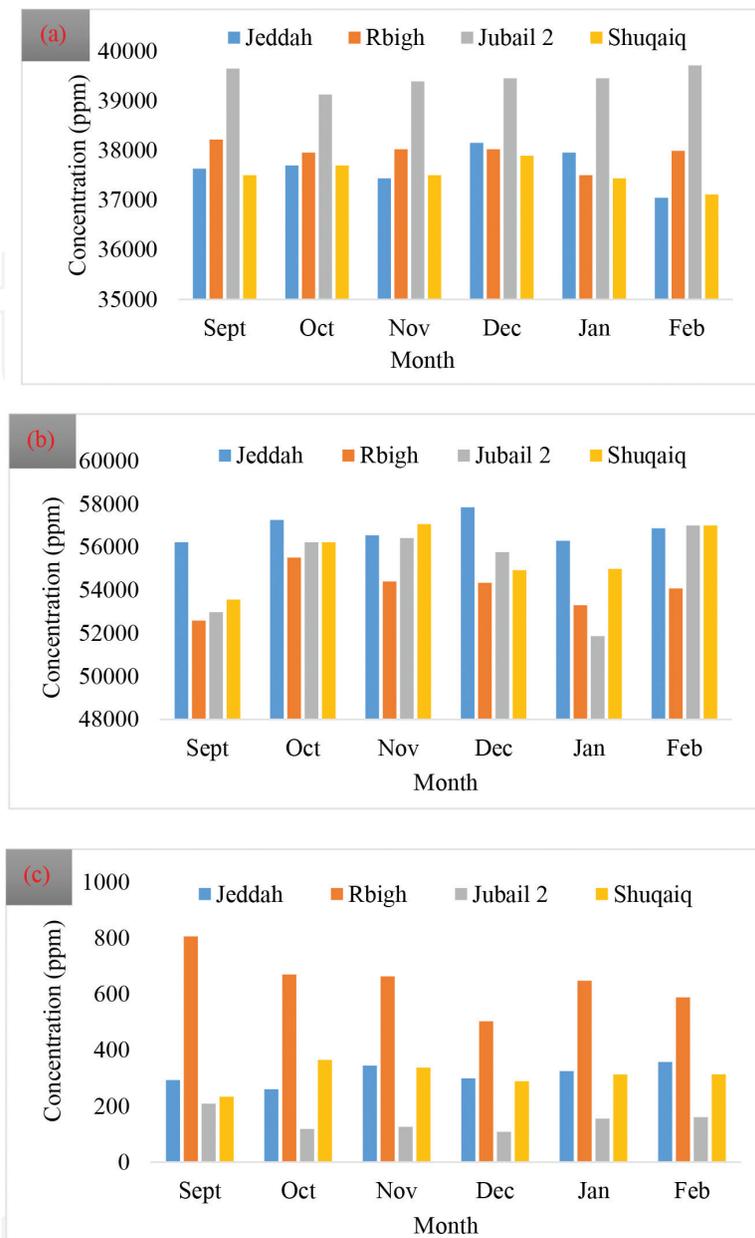


Figure 7. Six-month results of four major SWRO plants in Saudi Arabia. (a) Seawater feed concentration, (b) SWRO retentate concentration and (c) distillate concentration.

biomimetic membranes, isoporous block copolymer membranes and aligned nanotube membranes for energy efficiency [128–135]. In terms of commercialization, most of the proposed materials are farthest (5–10 years) from commercial reality. On the other hand, SWRO processes [136, 137] can be integrated with proposed AD cycle to improve process performance. Both technologies are readily available and can be implemented in near future.

3.2. Membrane process integration with AD cycle

Membrane process can be integrated with AD cycle for energy efficiency and to reduce environmental impact. AD cycle can operate at high concentration, almost near crystallization

Parameters	Quantity	Units
Total GCC capacity	26	Mm ³ /day
SWRO share (42%)	10.92	Mm ³ /day
Total primary energy (PE) consumption*	81.3	GWh/day
CO ₂ emission**	42,855.2	ton/day
Pre-treatment***		
Total feed (30% recovery)	36.4	mm ³ /day
Disinfection, NaOCl or free chlorine (1 ppm)	36.4	ton/day
Acid for pH adjustment, H ₂ SO ₄ (30–100 ppm)	3636.4	ton/day
Coagulation, FeCl ₃ or AlCl ₃ (1–35 ppm)	1272.7	ton/day
Flocculation, polyelectrolyte (0.2–4 ppm)	145.6	ton/day
Antiscaling, polycarbonic acid (2 ppm)	72.8	ton/day
Dechlorination, NaHSO ₃ (3 ppm)	109.2	ton/day

*SWRO electricity consumption = 3.5 kWh_{elec}/m³, Power plant conversion efficiency = 47%.

**CO₂ emission rate = 0.527 kg/kWh_{pe}.

***Pretreatment chemical values are taken from four plants and published literature [123–127].

Table 4. Energy consumption, CO₂ emission and chemical rejection by all SWRO plants in GCC. The severe impact on environment and marine life can be observed clearly.

zone, without fouling and corrosion chances due to low temperature operation. In addition to zero chemical injection, it also has minimal impact on environment as it operated with renewable energy. In this way, this hybridization will not only help to reduce CO₂ emission but also chemical rejection to the sea.

In proposed integration, the SWRO retentate, at 50,000 to 60,000 ppm, is supplied to AD cycle operating at evaporator temperature of 5–30°C. Both heat inputs, silica gel regeneration and evaporator, are supplied from renewable solar energy. This low evaporator temperature

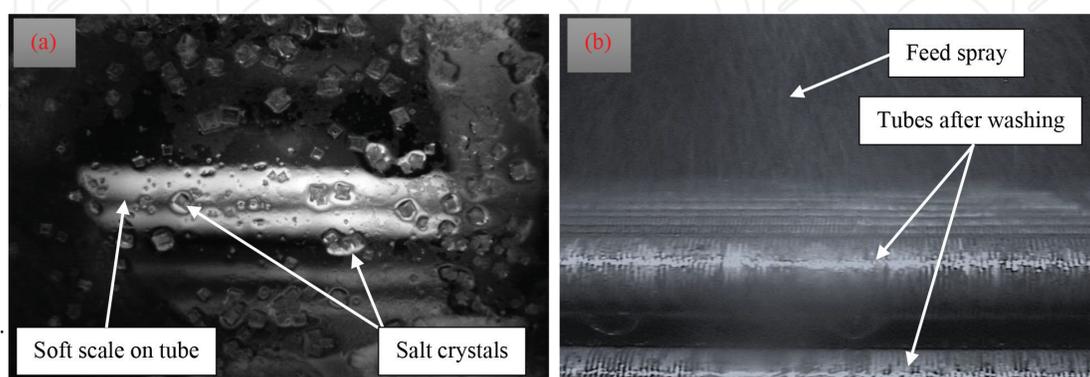


Figure 8. AD cycle evaporator inside view during operation. (a) Salt crystallization at 250,000 ppm at 10°C evaporator temperature and (b) white salt deposition cleared by feed spray jet impingement. It shows AD cycle successful operation at near crystallization zone, over 80% recovery: One of the highest recovery reported up till now.

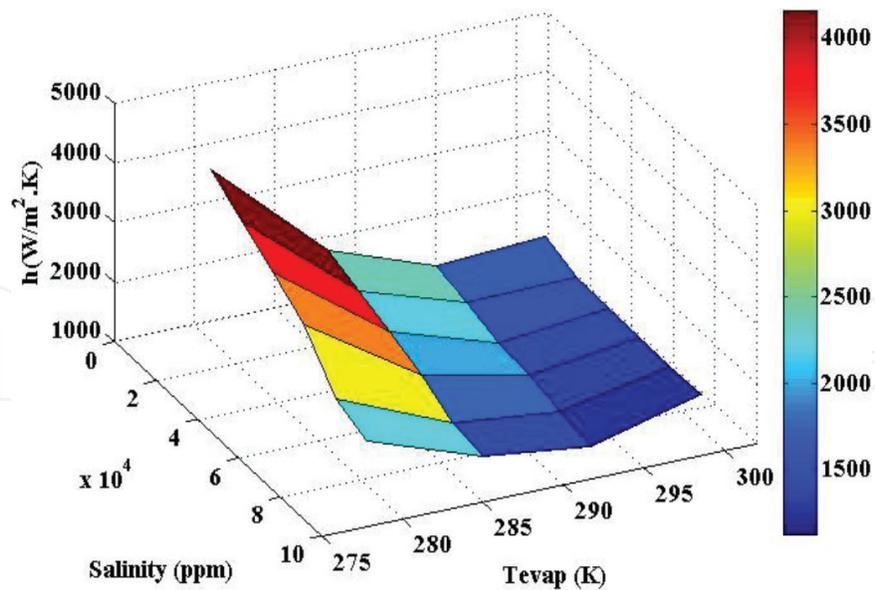


Figure 9. Effect of salt concentration and evaporator temperature on heat transfer coefficient of AD evaporator. The AD cycle evaporator can operate as low as 7°C.

enable AD cycle to operate more than 80% recovery, over 250,000 ppm. Experiments were conducted up to 250,000 ppm concentration to investigate salt concentration effect on heat transfer. **Figure 8(a)** shows salt crystallization in evaporator at 250,000 ppm. Soft scale deposition, in the form of white powder, was observed at high concentration that can be easily washed out by spraying as shown in **Figure 8(b)**. **Figure 9** shows concentration effect on heat transfer at different evaporator temperatures. It can be seen that even at high concentration the heat transfer coefficient has reasonable value that shows successful operation of AD cycle at highest concentration without fouling and scaling chances.

Parameters	SWRO	Hybrid cycle	% Saving by hybridization (%)
Total PE consumption ($\text{GWh}_{\text{pe}}/\text{day}$) [*]	81.3	40.9	98.9
CO_2 emission (ton/day)	42,855.2	21,550.1	98.9
Pretreatment chemicals (ton/day)			
Disinfection, NaOCl	36.4	13.4	170
Acid for pH adjustment, H_2SO_4	3636.4	1348.1	170
Coagulation, FeCl_3 or AlCl_3	1272.7	471.8	170
Flocculation, Polyelectrolyte	145.6	53.9	170
Antiscaling, polycarbonic acid	72.8	26.9	170
Dechlorination, NaHSO_3	109.2	40.4	170

^{*}AD electricity consumption = $1.38\text{kWh}_{\text{elec}}/\text{m}^3$ [137].

Table 5. Comparison of SWRO and its hybrid with AD cycle. The superiority of hybrid cycle can be seen clearly from summary table.

		Impact		
		1	2	3
Probability	1			
	2			
	3			
			SWRO (I × P)	Hybrid cycle (I × P)
Energy			3 × 3	3 × 1
CO ₂ emission			3 × 3	3 × 1
Chemical rejection			3 × 3	3 × 1
Brine concentration			3 × 2	3 × 2
Brine temperature			1 × 1	1 × 1
Pumps noise			3 × 2	3 × 2

Table 6. The comparison of impact of conventional SWRO and proposed hybrid cycle. The hybrid cycle reduced all parameters impact to medium and low.

The proposed AD cycle recovering 51% more from SWRO retentate booting overall recover to 81%. The final reject concentration was observed as 185,000 ppm from AD cycle. This integration will not only help to save overall energy but also environmental pollution. The summary of savings is presented in **Table 5**. It can be noticed that proposed integration can save up to 100% energy and CO₂ emission. In addition, it will also help to reduce chemical rejection to sea.

The impact matrix as presented in **Table 1** for conventional SWRO processes can be modified for hybrid cycle as presented in **Table 6**. It can be observed clearly that most of the parameters impact is reduced to medium and low from initial high value. This shows that hybridization will not help to produce more water but also with minimum impact on environment and marine life along with energy efficiency.

4. Thermal process and their integration: energy and environmental impact

The present share of thermally driven desalination processes is about 58% within the GCC countries. Typically, the energy requirements for such processes are reported as 2.0 kWh_{elec}/m³ electricity and 60–70 kWh_{th}/m³ of thermal energy. For energy efficiency, the thermally driven desalination processes are designed as an integral part of a cogeneration plant, producing both electricity and water from the temperature cascaded processes. The thermal energy is low-grade bleed steam extracted from the last stages of steam turbines. Based on the exergy destruction analysis of the primary energy input, the gas turbines consumed 75 ± 2% and steam turbines (via the heat recovery from turbine exhaust) extracted 21 ± 2% of input primary energy, leaving a mere 3 ± 1.5% of the total exergy input to the thermally driven desalination processes. Consequently,

Plant name	Capacity (m ³ /day)	Overall recovery (%)	Commissioning	Operator	Ref.
Ras Al Khair	728,000	40	2014	SWCC	[141–147]
Yanbu Phase-II	68,190	40	2012	SWCC	
Yanbu 1	100,800		1981	SWCC	
Yanbu 2	144,000		1999	SWCC	
Yanbu 2 expansion	68,190		2007	SWCC	
Yanbu 3	550,000	40	2016	SWCC	
Jubail 1	137,729	40	1982	SWCC	
Jubail 2	947,890	40	1983	SWCC	
Khobar 2	223,000	40	1982	SWCC	
Khobar 3	280,000	40	2002	SWCC	
Khafji	22,886	40	1986	SWCC	
Jeddah 4	221,575	40	1981	SWCC	
Shuaiba 1	223,000		1989	IWPP	
Shuaiba 2	454,545		2002	IWPP	
Shuqaiq	97,014		1989	SWCC	
Rabigh 2	18,000		2009	SWCC	
AlWajh 3	9000		1979	SWCC	
Umluj 3	9000		2009	SWCC	
Farasan 2	9000			SWCC	
AlQunfutha	9000			SWCC	
AlLith	9000			SWCC	
Alazizia	4500		1987	SWCC	
Rabigh 1	1204		1982	SWCC	
Future projects					
Jubail phase (3)	15,00,000	40	2021	SWCC	[148, 149]
Khobar 4	250,000		2020		
Khobar 5	220,000		2020		
Yanbu 5	100,000		2020		
Jubail 3	150,000		2021		

Table 7. Major thermal desalination plants in operation and future proposed projects in Saudi Arabia. They need only light pretreatment and can achieve 40% recovery.

the overall primary energy required by thermal desalination processes is merely 6.58 kWh_{pe}/m³ (equivalent of 4.25 kWh_{pe}/m³ from electricity +2.33 kWh_{pe}/m³ from the thermal input) [138–140]. We examine the major online thermal desalination plants in Saudi Arabia as well as the future proposed projects, and a summary of the analysis is outlined in **Table 7**.

Parameters	Quantity	Units
Total GCC capacity	26	mm ³ /day
Thermal share (68%)	17.7	mm ³ /day
Total primary energy (PE) consumption*	116.5	GWh/day
CO ₂ emission**	61,388.8	ton/day
Pretreatment		
Total feed	53.0	mm ³ /day
Scale inhibitor, polyphosphate (1–8 ppm)	424.3	ton/day
Acid, sulfuric acid (100 ppm)	5304.0	ton/day
Antifoam, poly othelyne ethylene oxide (0.1 ppm)	5.3	ton/day
Oxidizing agent, foam of chlorine (1 ppm)	53.0	ton/day

*Electricity consumption = 2.0 kWh_{elec}/m³, thermal energy consumption = 70kWh_{th}/m³, power plant conversion efficiency = 47%.

**CO₂ emission rate = 0.527 kg/kWh_{pe}.

***Pretreatment chemical values are taken from operational plants and published literature [150–154].

Table 8. Energy consumption, CO₂ emission and chemical rejection by all thermal desalination plants in GCC. Their impact is less severe as compared to SWRO.

All major integrated thermal desalination plants in Saudi Arabia are under SWCC and their recovery is about 40%. Since thermal desalination processes are robust, they need less chemicals as compared to SWRO processes. We analyzed the energy requirement, CO₂ emission and chemical rejection based on total capacity of GCC.

4.1. Thermal systems and hybrid cycle results and discussion

We analyzed the operational conditions of all major MED/MSF plants in the World and in Saudi Arabia. All mentioned MED plants are operating between top brine temperature (TBT) 60°C to bottom brine temperature (LBT) 40°C. The MSF operational range is slightly wider, between 120 and 40°C. The high temperature of MED/MSF is controlled by scaling and fouling chances and lower brine temperature is by ambient conditions. Limited range of operation put the cap on the performance of thermally driven desalination systems even they are dominating in GCC region. The detailed analysis of all thermal desalination plants in GCC and their impact are presented in **Table 8**.

It can be noticed that impact of thermal desalination processes is less severe than SWRO, but still same trend will have high impact in long-term operation. To maintain secure water supply in GCC, thermal desalination processes need to improve.

The two ways for thermal process improvements are material development for high heat transfer and process improvement to overcome thermodynamic limits of conventional processes.

The material development already reached to asymptotic limit, but processes improvement still have gap and need immediate research data for industrial application. We presented detailed experimentation on thermal system hybridization for industrial reference for future design.

4.2. Thermal process integration with AD cycle

Thermal desalination processes, MED/MSF, can be integrated with AD cycle to enhance their performance by extending their operational range. In these cycles, low temperature heat is supplied to first steam generator only and their performance depends on number of recoveries. The AD cycle hybridization can extend the last stage operational range to as low as 7°C as compared to conventional operational range of 40°C. This extension of LBT helps to insert more number of recoveries and hence boosts the performance.

To investigate hybrid MED performance, a four-stage MED was designed, fabricated and installed in KAUST. This MED is a miniature form of Yanbu MED plant installed by Doosan, Korea. The last stage of MED was integrated with solar thermal-driven AD cycle to extend last stage temperature to below ambient condition. **Figure 10** shows AD and MED pilots installed in KAUST, Saudi Arabia.

The AD regeneration heat, 65°C hot water, is supplied from evacuated tube solar thermal collectors installed on one of the rooftop building. Experiments were conducted with straight MED as well as the hybridized MED + AD cycle to compare the performance. **Figure 11(a)** shows the control of MED pilot. For MED heat source, a small boiler is installed to inject steam into hot water circuit to maintain any set temperature. Feed is supplied parallel to all four stages after extracting condensation heat from last condenser. Distillate and brine are collected in separate tanks via u-tube to maintain the inter-stage pressure difference. Straight MED experiment was conducted for 72 hours continuously to validate the stability of operation. The temporal profile of all components showed stable operation of MED as presented in **Figure 11(b)**. After successful MED testing, it was hybridized with AD cycle to operate as a hybrid cycle. Integration

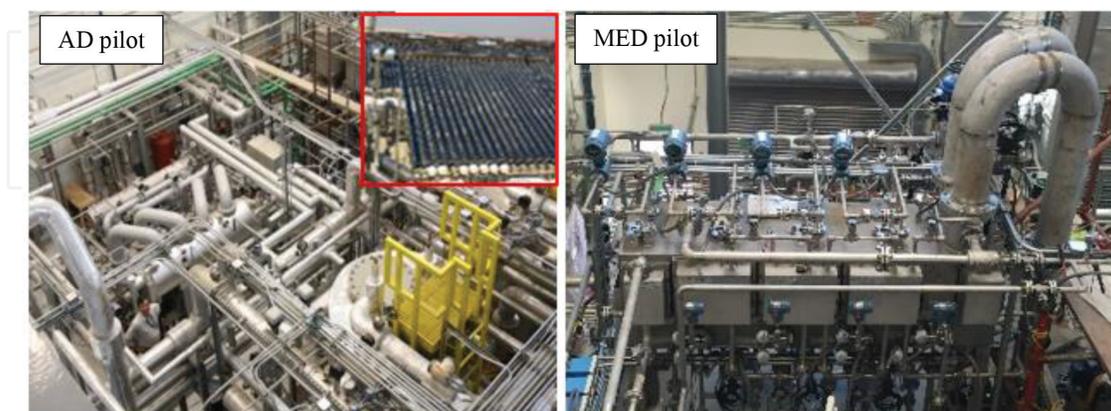


Figure 10. Solar-driven AD pilot and four-stage MED plant to investigate as a hybrid cycle. The pilot plant was designed for overall capacity of 10 m³/day.

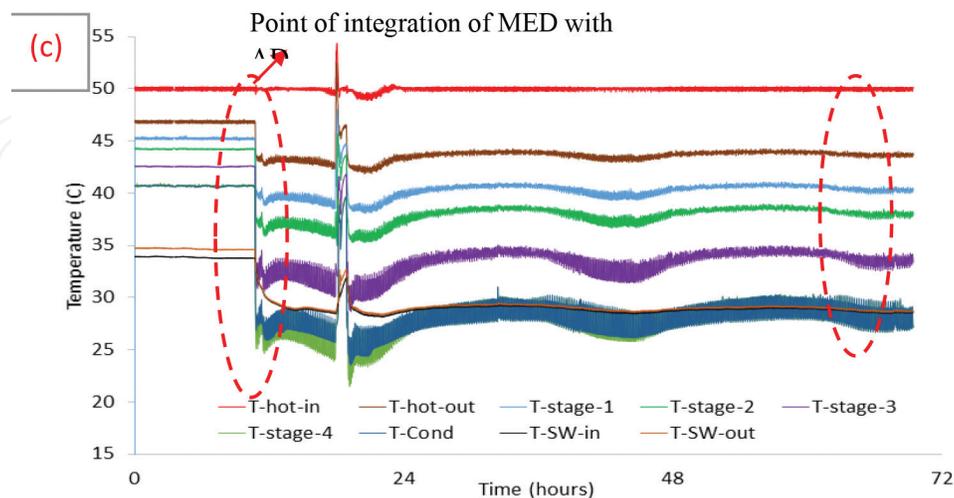
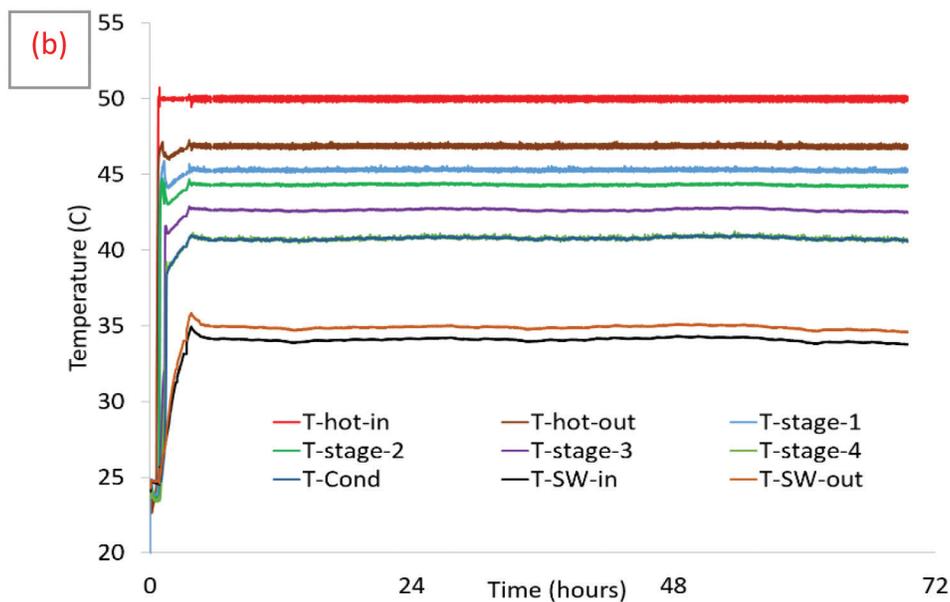
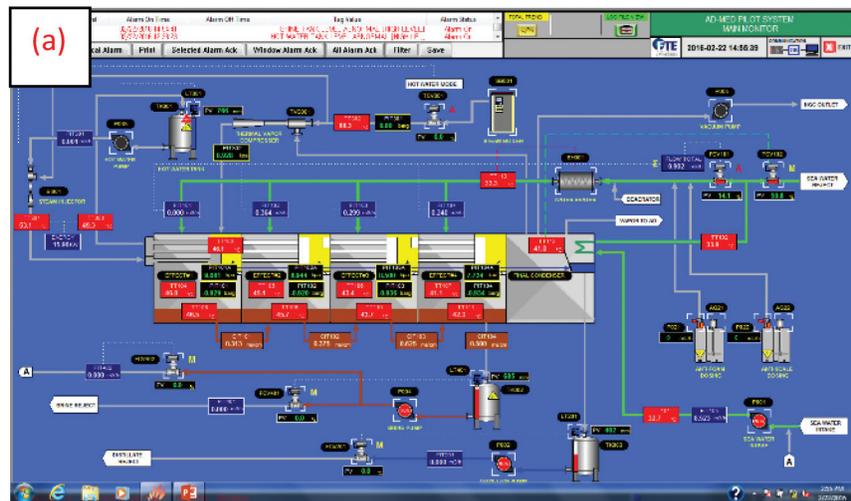


Figure 11. MED and AD pilot results installed in KAUST. (a) Control of MED pilot and (b) straight MED components temperature profiles. Inter-stage temperature varies 2–3°C for 72-hour experiment, (c) MED hybrid cycle components temperature profiles. Inter-stage temperature increased to almost double as compared to straight MED. Also, hybrid cycle can operate below ambient temperature as can be seen last stage temperature.

of AD cycle to the last stage of MED bring down the last stage temperature to below ambient and also inter-stage temperature was observed as 5–6°C as compared to 2–3°C in case of straight MED as shown in **Figure 11(c)**. The excellent thermodynamic synergy of hybridization of two thermally driven cycles boosted water production to more than twofold as compared to straight MED at same top brine temperature. **Figure 12** shows the water production comparison of straight MED and hybrid MEDAD. It can be clearly seen that water production improvement is more than two times by AD cycle integration with last stage of MED.

Based on thermal cycle hybrid results, the impact matrix has been revised and presented in **Table 10**. The hybridization greatly improved the energy efficiency and reduced the environmental impact as compared to conventional processes. In GCC, to maintain the confidence on thermally driven desalination processes, their hybridization is very important. It will help to achieve future water targets to maintain the GDP growth but following the COP21 goals for environmental emission.

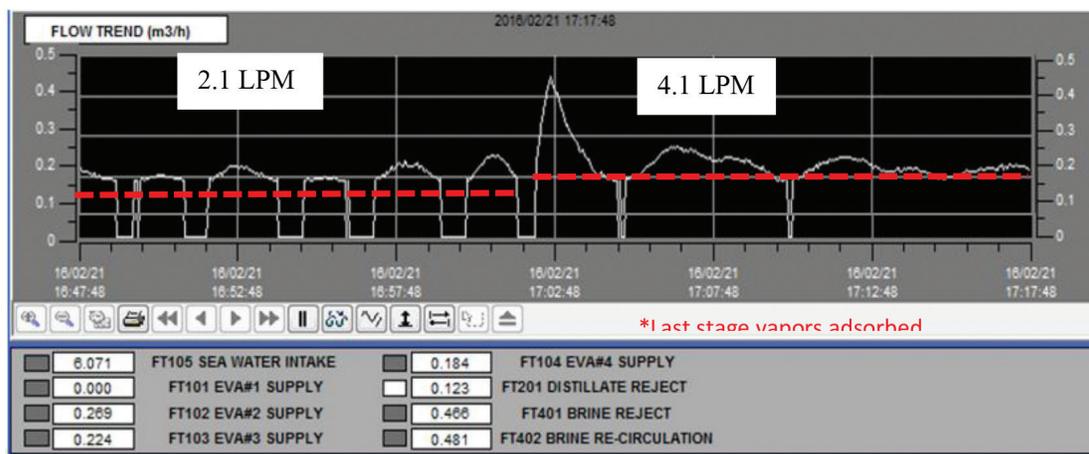


Figure 12. MED and hybrid MEDAD cycle water production comparison. Integration of AD to the last stage of MED can boost water production to twofold by extending inter-stage temperature (**Table 9**).

Parameters	Thermal system	Hybrid cycle	% Saving by hybridization (%)
Total PE consumption (GWh _{pe} /day)*	116.5	84.2	38.3
CO ₂ emission (ton/day)	61,388.8	22,373.1	38.3
Pretreatment chemicals (ton/day)			
Scale inhibitor, polyphosphate	424.3	235.7	80
Acid, sulfuric acid	5304.0	2946.7	80
Antifoam, poly othelyne ethylene oxide	5.3	2.95	80
Oxidizing agent, foam of chlorine	53.0	29.47	80

*AD electricity consumption = 1.38 kWh_{elec}/m³.

MEDAD hybrid cycle improvement factor = 2.0 [155–173].

Table 9. Comparison of thermal desalination and its hybrid with AD cycle. The superiority of hybrid cycle can be seen clearly from summary table.

		Impact		
		1	2	3
Probability	1			
	2			
	3			
			Thermal (I × P)	Hybrid cycle (I × P)
Energy			3 × 3	3 × 2
CO ₂ emission			3 × 3	3 × 1
Chemical rejection			3 × 2	2 × 1
Brine concentration			3 × 1	3 × 2
Brine temperature			1 × 1	1 × 1
Pumps noise			2 × 1	2 × 1

Table 10. The comparison of impact of conventional thermal desalination system and proposed hybrid cycle. The hybrid cycle reduced all parameters impact to medium and low.

5. Conclusions

An efficient and environment-friendly hybrid desalination process has been demonstrated for the first time with different energy mix for future water supplies. The following advantages can be observed clearly by implementation of desalination hybridizations:

- I. Energy consumption and chemical discharge saving up to 99% and 150%, respectively, by the SWRO hybridization with AD cycle.
- II. Thermal process integration with AD cycle will save up to 38% energy and up to 80% chemical rejection to sea.
- III. CO₂ emission saving by SWRO+AD up to 99% and by MEDAD up to 30%.
- IV. Overall recovery up to 80% can be achieved without scaling and fouling chances due to low temperature operation.
- V. Integration will help to reduce overall impact to low or moderate level, acceptable level under COP21 goal.
- VI. Integration will help to secure future water demand for expected GDP growth rate with minimal impact on environment and by implementing different energy mix for higher energy efficiency.

We opine that the higher energy efficiency of hybridized seawater desalination cycles can contribute to meeting the goals of sustainable seawater desalination as outlined under a sub-section of the COP21.

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Abbreviations

COP	Conference of parties
IEO	International Energy Outlook
OECD	Organization for Economic Cooperation and Development
Btu	British thermal unit
BAU	Business as usual
GCC	Gulf Cooperation Council
SWRO	Seawater Reverse Osmosis
MED	Multieffect desalination
MSF	Multistage flash
AD	Adsorption cycle

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