Northumbria Research Link

Citation: Alrowais, Raid, Shahzad, Muhammad Wakil, Muhammad, Burhan, Bashir, MT, Chen, Qian, Xu, Bin, Kumja, M., Markides, Christos N. and Choon, Ng Kim (2022) A thermally-driven seawater desalination system: Proof of concept and vision for future sustainability. Case Studies in Thermal Engineering, 35. p. 102084. ISSN 2214-157X

Published by: Elsevier

URL: https://doi.org/10.1016/j.csite.2022.102084 <https://doi.org/10.1016/j.csite.2022.102084>

This version was downloaded from Northumbria Research Link: http://nrl.northumbria.ac.uk/id/eprint/49027/

Northumbria University has developed Northumbria Research Link (NRL) to enable users to access the University's research output. Copyright © and moral rights for items on NRL are retained by the individual author(s) and/or other copyright owners. Single copies of full items can be reproduced, displayed or performed, and given to third parties in any format or medium for personal research or study, educational, or not-for-profit purposes without prior permission or charge, provided the authors, title and full bibliographic details are given, as well as a hyperlink and/or URL to the original metadata page. The content must not be changed in any way. Full items must not be sold commercially in any format or medium without formal permission of the copyright holder. The full policy is available online: http://nrl.northumbria.ac.uk/policies.html

This document may differ from the final, published version of the research and has been made available online in accordance with publisher policies. To read and/or cite from the published version of the research, please visit the publisher's website (a subscription may be required.)

Northumbria University NEWCASTLE

CUSTOMER SERVICE EXCELLENCE CSE

UniversityLibrary

A Thermally-Driven Seawater Desalination System: Proof of Concept and Vision for Future Sustainability

Raid Alrowais[1], Muhammad Wakil Shahzad[2*], Muhammad Burhan[3], MT Bashir[4], Qian Chen[3], Ben Bin Xu[2], M. Kumja[3], Christos N. Markides[5] and Kim Choon Ng[3]

[1] Department of Civil Engineering, Jouf University, Sakaka 72388, Saudi Arabia
[2] Mechanical and Construction Engineering Department, Northumbria University, Newcastle Upon Tyne NE1 8ST, United Kingdom
[3] Water Desalination and Reuse Center, King Abdullah University of Science and Technology, Saudi Arabia
[4] CECOS University of IT and Emerging Sciences, Peshawar, Pakistan
[5] Clean Energy Processes (CEP) Laboratory, Department of Chemical Engineering, Imperial College London, London, UK

*Corresponding authors: muhammad.w.shahzad@northumbria.ac.uk and rnalrowais@ju.edu.sa

Abstract

Since the 1970s, commercial-scale thermally-driven seawater desalination plants have been powered by low-grade energy sources, drawn either with low-pressure bled-steam from steam turbines or the solar renewable energy harvested that are supplied at relatively low temperatures. Despite the increasing trend of seawater reverse osmosis plants, the role of thermal desalination methods (such as multi-stage flashing and multi-effect distillation) in GCC countries is still relevant in the Arabian Gulf, arising from higher salinity, the frequent algae blooms of seawater and their ability to utilize low temperature heat sources. Given the urgent need for lowering both the capital and operating costs of all processes within the desalination industry and better thermodynamic adaptation of low-grade heat input from renewable sources, the present paper addresses the abovementioned issues by investigating the direct contact spray evaporation and condensation (DCSEC) method. A DCSEC system comprises only hollow chambers (devoid of membranes or tubes, minimal use of chemical and maintenance) where vapor generation (flashing) utilizes the enthalpy difference between the sprayed feed seawater and the saturated vapor enthalpy of the vessels. Concomitantly, vapor is condensed with spray droplets of cooler water (potable) in adjacent condenser vessels, employing a simple design concept. We present detailed design and real seawater experiments data of a DCSEC system for the first time. The water production cost is calculated as \$0.52/m^3, which is one of the lowest figures reported compared to commercial processes presented by Global Water Intelligence.

Keywords: DCSEC system; Thermal Desalination; Experimental Study; Sustainable Desalination; Thermal Energy Storage

1. Introduction

Three-quarter of the earth's surface area is covered by seawater, which is impaired by dissolved salts, algae, etc., and less favorable for potable propose. However, freshwater is vital for human survival and it is a necessary resource for economic development of all countries, particularly in the agriculture, manufacturing, and industrial sectors. As reported recently [1-3], the increasing demand of freshwater globally is caused by the rapid population growth and economic development.

Owing to hot desert climate conditions in Gulf Cooperation Council (GCC) countries, freshwater availability from rivers and lakes are scare due to limited rainfall, less than 150 mm annually. However, regional variation of rainfall along the Red Sea and the Gulf of Oman may vary up to 500 mm, as shown in Table 1 [4, 5]. On other hand, the ground water reserves of GCC countries are estimated to be around 2300 billion cubic meters (bcm) and of which 300 bcm has already been extracted for human activities. If the current rate of extraction continues, it is projected that remaining ground water of the region will be depleted in less than 2 decades [6].

Table 1. Summary of water resources for GCC countries [4, 5].

Country	Area (km^2)	Population (million)	Average annual rainfall (mm)	Average annual freshwater availability (m^3/capita)	Renewable water resources (million cubic meter, Mm^3)
Bahrain	652	1.7	85.5	70.5	100.2
Kuwait	17,818	4.3	110.3	5.2	160.1
Oman	212,460	5.1	240.6	275.3	1468.0
Qatar	11,610	2.9	75.5	20.6	86.4
KSA	2,149,690	34.8	290.2	70.7	6080.0
UAE	83,600	9.9	120.5	16.1	315.0

As mentioned in the introductory paragraph, the regional population growth is a major contributing factor for high potable water consumption. From 1950 to 1990, the GCC has recorded to be one of the highest population growth regions where its population has doubled from 17.8 to 33.5 million. It is projected that the GCC population will reach over 70 million by the next decade [5]. Beside population growth, water demand is also a function of economic activity of countries as shown in Figure 1 [7]. Despite the increasing trends of water demand and Gross domestic product (GDP), the water use intensity per thousand GDP depicts a decreasing trend indicating improvement in water utilization by higher economic GDP, as shown in Figure 2[8].

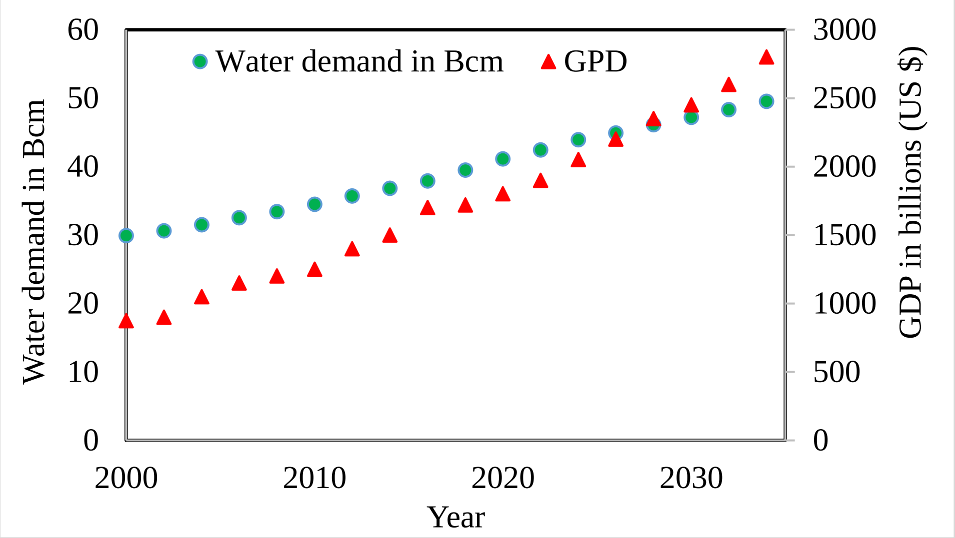


Figure 1. Historical and projected water demand and GDP of GCC countries.

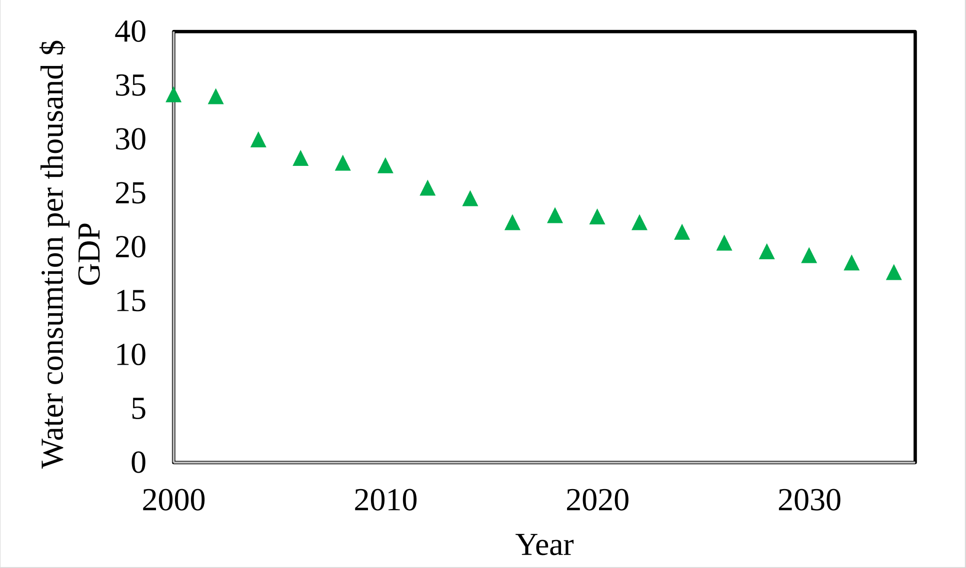


Figure 2. Historical and projected water consumption intensity of GCC countries.

In view of the increasing trend of freshwater demand, seawater desalination is considered as one of the most feasible and practical sources of potable water supply in meeting the water scarcity of GCC countries. Presently, the global installed desalination capacity is growing exponentially, producing over 100 million cubic meters of freshwater per day from the estimated 19,000 desalination plants [9, 10]. However, more than half seawater desalination plants of the world are installed in the Middle East and GCC countries, as shown in Figure 3 [11].

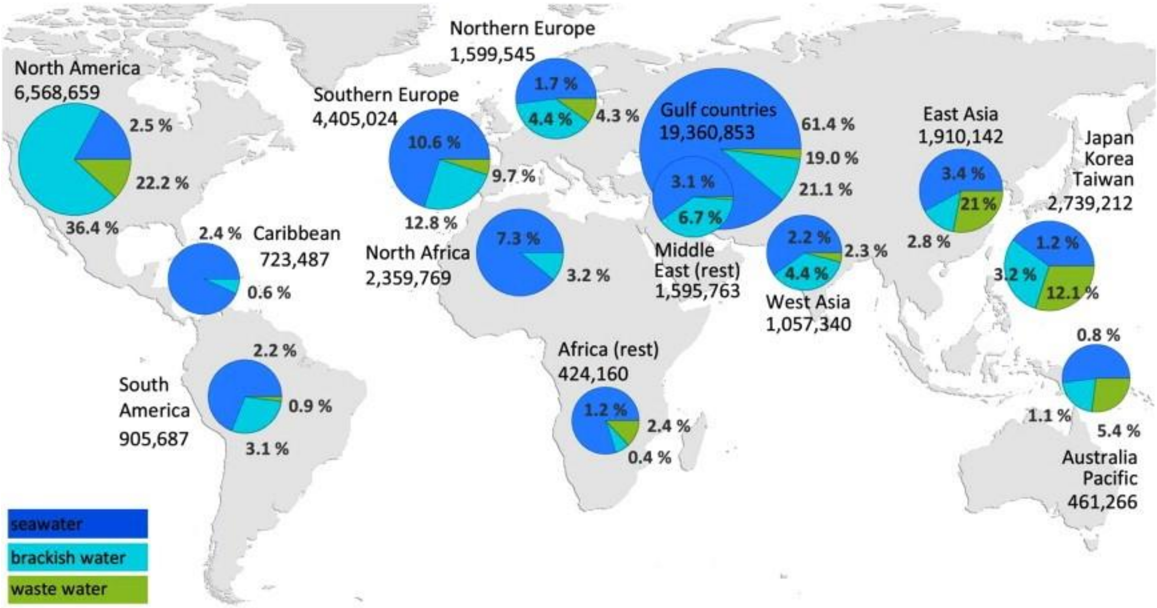


Figure 3. Global distribution of desalination capacities worldwide [11].

Hitherto, two major types of seawater desalination technologies are widely installed, i.e., thermally driven and membrane processes [12, 13]. In thermal desalination, the separation of impurities and dissolved solids from seawater is achieved through the supply of low-grade thermal energy for evaporation and followed by the condensation processes under full saturation states of plants. Due to higher salinity, temperature, turbidity, and the frequent occurrences of algae blooms of surrounding seawater of GCC countries [14], the thermal processes, namely the multi-stage flash desalination (MSF) and the multi-effect desalination (MED), are dominantly used for practicality. On the other hand, the seawater reverse osmosis (SWRO) processes utilize high pressure seawater feed to overcome the osmotic pressures of solute concentration difference across the membranes. Although SWRO method has been widely use in other part of the world, due to favorable seawater feed conditions, but it has yet to be proven for long-term (plant life) sustainable desalination in the environment of harsh conditions of GCC seawater.

Many hybrid processes are also introduced such as MEDAD [15-19], MSF-MED [20-22] and RO-MSF [23-35] to overcome individual processes operational limitations. Thermodynamic synergy of thermally driven processes improved their performance in hybrid configuration while membrane process integration improved overall recovery.

From the perspectives of plant owners and consumers, one of the major concerns is the overall unit cost of water production from the available desalination plants, that are normally expressed by capital (CAPEX) and operation (OPEX) costs. Recent reports by Global Water Intelligence [36] presented the average assorted categories of the CAPEX and OPEX, as shown in Figure 4. Such unit water costs were analyzed by GWI over the lifespan of plants, expressed in terms of US$ per cubic meter of water produced. It can be noticed that the total unit cost of water produced for MSF, MED and SWRO are $1.023, $0.738 and $ 0.749 respectively. On closer examination of the tabulate data of CAPEX/OPEX, i.e., $0.42/$0.603 for MSF, $0.29/$0.448 for MED and $0.290/$0.450 for SWRO, the respective itemized cost of water is relatively high for achieving the goal of sustainable desalination. Hence, the motivation of this paper is to address the unit cost of desalinated water from the viewpoints of high CAPEX and OPEX of desalination plants. The sections below describe the innovative direct-contact spray evaporation and condensation (DCSEC) approach to seawater desalination.

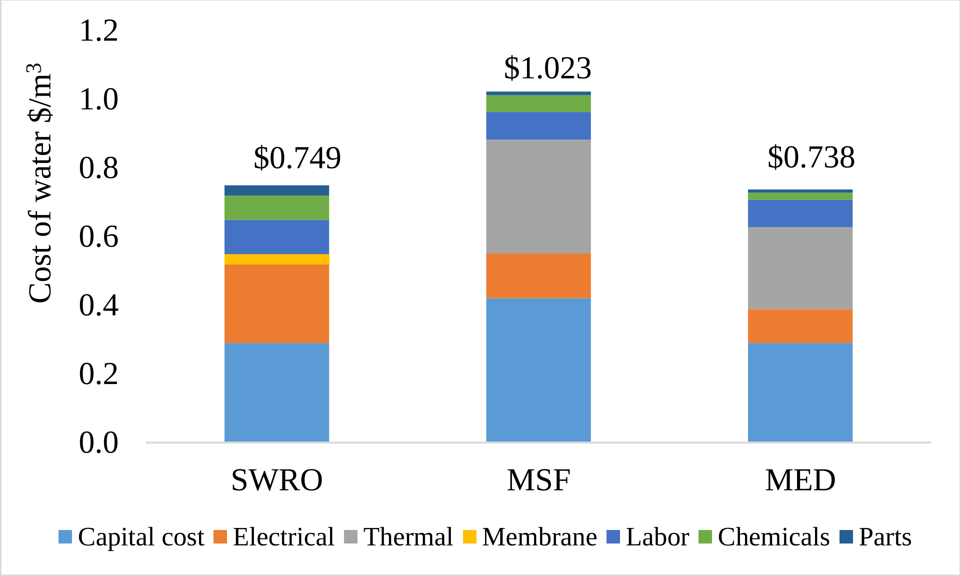


Figure 4. Itemized unit cost of desalinated water for CAPEX and OPEX of assorted types of practical desalination plants [36]. Average price of kWh electricity (2018) = US$0.16.

2. Direct-contact spray evaporation and condensation (DCSEC)

DCSEC is not new as it has been reported since 1980s. However, the methodology did not gain popularity in desalination industry due to two major factors. Firstly, the temperature difference between feed water and equilibrium saturated temperature of vessels is large, typically greater than 10 K. This high temperature difference limit the number of stages for a given finite available top- and bottom-brine temperatures and hence water production. Secondly, the rate of flashing phenomena from water droplets, which depends on available surface area of a droplet, has reached a local (defined by droplet size) asymptotic level giving correspondingly a low water vapor production rate. In 1981, Miyatake et al. [37, 38] first reported the spray flash evaporation distillation system. In their experimentation, hot water feed at 40-80 °C were injected into low-pressure vapor zone of the flash chamber. Based on the results, an empirical formula for dimensionless temperature of spray jet was obtained, defining the characteristics of spray flash evaporation. In 2006, Ikegami et al. [39] compared the performance between upward and downward jets and observed better flash evaporation processes with shorter travel distance of feed in the evaporator chamber. Subsequently in 2009 and 2010, Mutair and Ikegami [40] conducted similar flash evaporation studies using upward jets but with larger nozzles. They found that the intensity of flash evaporation increased with higher initial water temperatures and the degree of superheat. El-Fiqi et al. [41] conducted similar experiments with diameters of spray nozzles up to 0.4 mm, whilst an injection pressure of up to 6 bar was used. They measured the degree of superheat ranges from 2 K to 18 K with the feed water temperatures from 40 to 70 °C at assorted flow rates. Chen et al. [42-44] also simulated the droplet evaporation processes in a single-stage configuration and observed the relationship between increasing water productivity with initial droplet velocity. They highlighted that smaller droplet of feed are essential parameters for enhancing the evaporation processes. The above-mentioned work was, unfortunately, conducted with pure water as feed. This paper presents DCSEC design and experimentation using actual seawater as feed drawn directly from the Red Sea. The details of experimental system design and experimentation are presented in the sections to follow.

3. DCSEC experimental facility

A lab-scale DCSEC desalination system has been designed, fabricated, and installed at laboratory LFO 155 of King Abdullah University of Science Technology (KAUST). The schematic of pilot is presented in Figure 5 and actual pilot is shown in Figure 6. It comprises the hollow chambers of evaporator and condenser, along with other supporting external components such as a heater, pumps, heat exchanger, feed tank, and distillate tank. To eliminate salt carryover, demister is installed in between evaporator and condenser chamber. In this design, no physical components or interfaces were used for separation, for example, the porous membrane used in SWRO plants or heat exchanger tubes in MSF and MED. Consequently, the DCSEC has much lower CAPEX as compared to conventional desalination methods. Its simple design minimized scaling with ease of operation and hence, it has the ability to handle seawater at high salinity up to 200,000 ppm. The other advantage of DCSEC is the ability to use a low grade or temperature heat source, and consequently, it has to operate under partial vacuum pressure conditions corresponding to the saturated temperatures of the vessels.

For testing, after successful vacuum leakage test, system was prepared for real seawater experimental test. Desired vacuum pressure in evaporator, condenser and auxiliary chambers such as feed, distillate, and brine were obtained using oil driven vacuum pump. At same time, seawater and potable water valves were open to evaporator and condenser. The feed and potable water pumps were turned on for circulation together with the electric heater to raise the evaporator's feed water temperature. The evaporator temperature was controlled using a thermistor controller and a chilled water heat exchanger was installed to attain the condenser's desired temperature. A data logger was used to log all parameters such as temperature, pressure and flow rates at different location on pipelines. Distillate production from the condenser chamber was also measured with a computer logged weighing machine. Upon completing the first experiment for certain time interval, the feed seawater's supply temperature was raised by changing the heater element's electrical voltage and second test was conducted. These operating and control procedures were repeated for all test matrices and configurations. Design and operational parameters are given in Table 2. The DCSEC system was flushed with fresh water for 1 hour at end of day to maintain the integrity of components (made of stainless steel 316L) from seawater's aggressive characteristics.

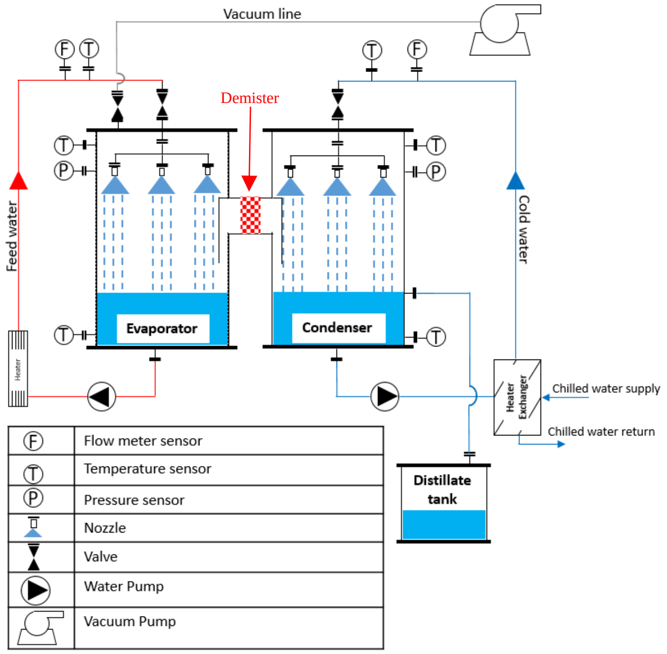


Figure 5. Schematic diagram of direct contact spray-assisted evaporation (DCSEC) experiment facility at KAUST, Saudi Arabia.

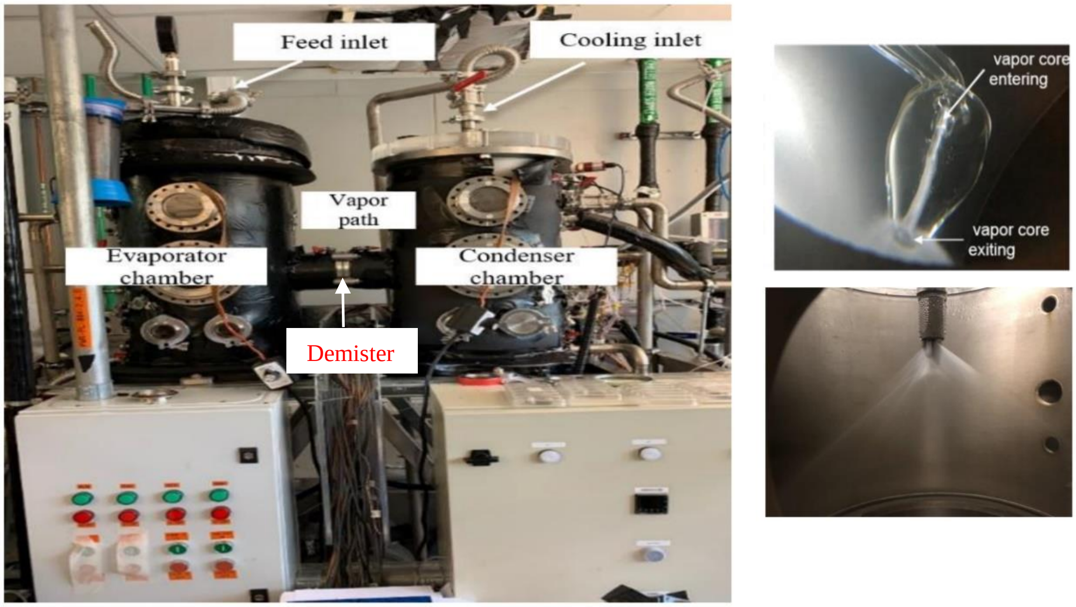


Figure 6. Direct contact spray-assisted evaporation (DCSEC) experiment facility at KAUST, Saudi Arabia.

Table 2. Detailed design and operational parameters of DCSEC experimental facility.

Parameters	**Evaporator**	**Condenser**
Height (mm)	700	700
Diameter (mm)	640	640
Materials	Stainless steel 316L	Stainless steel 316L
Thickness **(**mm**)**	6	6
View ports	ISO 100, IS0 150	ISO 100, IS0 150
Temperature range	35-60 °C	20-50 °C
Flow rate	Feed water: 2 L/h	Cold water: 10 L/h
Demister: DP type, round wire 0.08mm diameter, Density 128kg/m^3, surface area 403m^2/m^3		

4. Results and discussion

Owing to the wide range of temperature difference (Δ *T*) across the single-stage evaporator and condenser, three sets of temperature differences between the chambers were adopted, namely 3-4 K, 5-6 K, and 7-8 K. For each Δ*T* range, the temperature of the heated seawater supplied to the evaporator was controlled from 35 ± 0.5 °C to 60 ± 0.5 °C at increasing temperature intervals of 5 °C per test run. To maintain the set Δ*T* of chambers, the condenser rejected heat to the ambient was achieved by regulating chilled water flowrates to heat exchanger. Due to the large thermal mass of the chambers, each experiment took 30 min to reach a steady-state, and the distillate measurement were recorded over the next 180 min.

For each feed inlet temperature to evaporator, the temperature difference of vapor between evaporator and condenser was manually controlled by adjusting the heat rejection rate of condenser to the ambient. These tests were conducted over the mentioned temperature up to 60 °C for both types of potable and seawater and concomitantly, the distillate were collected on the weighing balance. It is noted that the distillate production for seawater were generally lower up to 3.5% than those similar experiments obtained with potable water, due mainly to the effects of the boiling point elevation of seawater. For design purposes, each distillate production is normalized with evaporator volume that is L/h.m^3. It is seen from the Table 3 that at the feed temperature of 60 °C with a Δ*T* of 7-8 K, the maximum distillate production recorded were 8.97 and 9.28 L/h.m^3 for seawater and potable water respectively. A summary of test results for all key parameters affecting the performance of DCSEC desalination method are shown in Table 3.

Table 3. Summary of the distillate flow rates in liter per hour per unit volume of evaporator (L/h.m^3).

	Potable water					Seawater				
	$T_{f,eva}$ (^oC)	$T_{v,eva}$ (^oC)	$T_{f,con}$ (^oC)	$T_{v,con}$ (^oC)	Distillate (L/h.m^3)	$T_{f,eva}$ (^oC)	$T_{v,eva}$ (^oC)	$T_{f,con}$ (^oC)	$T_{v,con}$ (^oC)	Distillate (L/h.m^3)
ΔT (3-4) K	35.4	29.9	27.5	26.4	1.0	35.4	32.2	29.0	28.8	1.0
	40.1	35.9	32.2	32.8	2.3	40.2	36.0	31.1	32.1	2.3
	45.1	39.8	36.3	36.2	2.7	45.2	38.7	32.8	35.2	2.6
	50.1	42.7	38.4	39.2	3.1	50.1	42.5	37.6	39.0	3.0
	55.6	48.1	44.3	44.5	5.5	54.8	46.6	40.9	43.2	5.3
	60.1	52.9	48.3	49.4	6.3	60.1	51.8	46.9	47.8	6.1
ΔT (5-6) K	35.4	31.3	25.8	25.1	1.2	35.7	31.3	25.1	26.3	1.1
	40.2	35.2	29.2	29.3	3.0	40.4	34.0	27.1	28.6	2.9
	45.1	38.0	31.0	32.0	3.6	45.2	35.7	27.5	30.4	3.4
	50.1	40.7	34.2	35.3	5.0	49.5	39.0	30.4	33.7	4.9
	55.0	46.0	37.5	40.4	6.7	54.8	43.4	34.9	37.8	6.4
	60.0	49.4	41.6	43.9	8.0	59.4	46.5	38.8	41.0	7.7
ΔT (7-8) K	35.2	29.5	20.0	21.6	1.9	35.9	32.5	24.3	25.2	1.8
	40.2	32.8	24.0	25.1	4.2	40.4	35.2	25.5	27.9	4.1
	45.1	36.3	26.9	28.8	6.8	45.4	37.1	27.2	29.2	6.5
	50.2	41.5	32.2	33.7	7.1	49.6	39.1	28.4	31.5	6.8
	55.5	45.5	36.1	38.2	7.6	55.3	42.0	32.2	34.8	7.3
	60.2	50.8	41.9	42.7	9.2	59.6	48.5	37.9	41.0	8.9
Evaporator volume: 0.225 m^3 , Condenser volume: 0.225 m^3										

Alternatively, a pictorial and succinct trend of DCSEC distillate production with the respect to the temperatures of potable and seawater feed, but at the highest temperature difference (ΔT of chambers) of 7-8 K, can be seen from Figure 7. Also from Figure 8, it is observed that the distillate production from flashing (L/h.m^3) is linearly proportional to the temperature difference between the seawater feed and saturation temperature of evaporator chamber. Furthermore, the onset of liquid flashing into vapor could only commence after a minimum threshold of 3 K, caused by the presence of non-equilibrium phenomena such as heat transfer resistances and temperature depression of salt concentration.

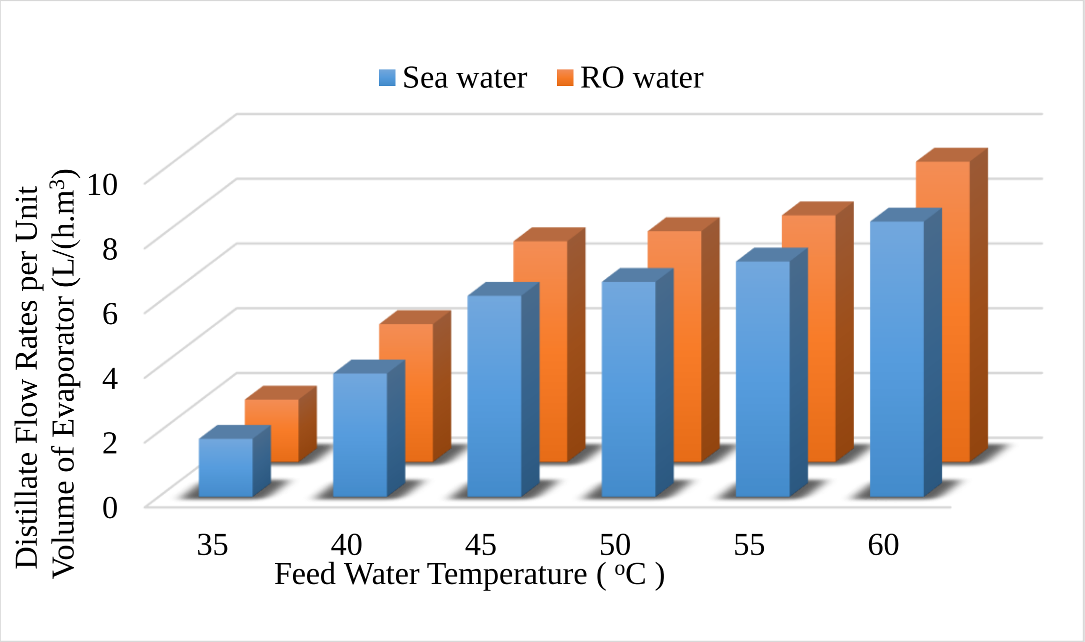


Figure 7. Comparison of seawater and potable water in DCSEC experiments at the same boundary conditions. The feed flow rate for all tests was set at 129 L/h.

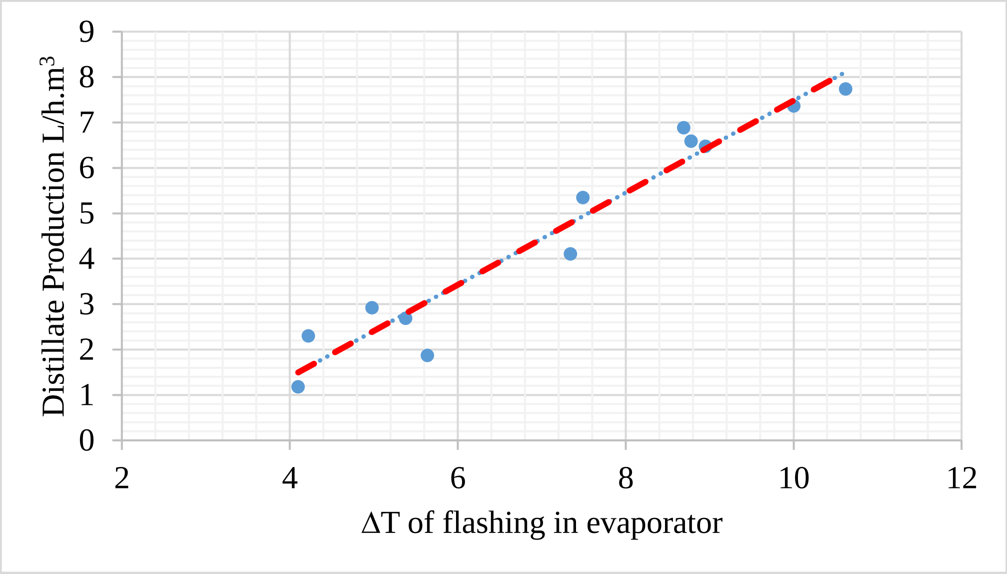


Figure 8. Flashed water production rate for assorted temperature differences between feed and evaporator chamber.

Lastly, distillate water quality was also analyzed, and percentage rejection of various components was calculated as presented in Table 4

Table 4: Distillate water quality from DCSEC system

Component	Ion form	Seawater supply (ppm)	Distillate quality (ppm)	Rejection percentage
Sodium	Na^+	10545	3.1	99.9%
Potassium	K^{+2}	510.5	0.085	
Calcium	Ca^{2+}	418.5	0.014	
Magnesium	Mg^{2+}	1450.0	0.018	
Chloride	Cl^-	22.5	0.006	
Sulfate	SO_4^{2-}	2.9	0.0007	

5. Thermo-economic analysis

Thermo-economic analysis combines energy analysis and economic principles to determine the unit cost of water in terms of capital (CAPEX) and operation (OPEX) costs. Based on the plant design comprising: (i) daily water production capacity in cubic meter, (ii) life-span of plant and (iii) interest rates for capital resources, the amortization of capital cost is performed with the capital recovery factor (CRF) method. The operation cost is determined by summing the yearly recurring costs of: (i) thermal energy input, (ii) parts replacement, (iii) chemical used for water treatment, (iv) electricity consumption of desalination and accompanying applications and (v) labor cost. Table 5 depicts the key design parameters of DCSEC with production of 25,000 m^3/day. These are guessed parameters based on our pilot experimentation. Actual performance may vary as per design and operation. Of these parameters, the two salient parameters of design are the DCSEC distillate production rates [45] and the percentage of heat recovery that could be achieved experimentally. The computed performance ratio (PR: ratio of distillate produced to energy input) of six-stages DCSEC with enhanced heat recovery of condensation energy and micro-bubbles augmentation in distillate production is found to be 9.2 [45]. Microbubbles enhance nucleation sites and hence boost the surface flash evaporation. The embedded microbubbles water droplets enhance surface flashing/evaporation due to increased surface area at lower temperature differential 3-4C as compared to 8-15C without microbubble.

Table 5. Design parameters of DCSEC with production of 25,000 m^3/day.

Volume of evaporator (DCSEC) (m^3)	4,000
Average velocity of trajectory (m/s) [45]	3-4
Seawater Feed temperature TBT (ºC)	60
Water inlet temp. of condenser (ºC)	25
Yearly interest rate (%)	1.5
DCSEC distillate production rate (L/h.m^3)*	55.8
**Fraction heat of recovery from 6-stages design	0.5
Life span (years)	30
No. of pumps	6+2
Feed to distillate flow factor (-)	5.5
Distillate production (m^3/day) from 4000 m^3 chamber volume	25,000
Total height of pump per stage (m)	5.7
Performance Ratio (PR) for six stages with heat recovery and micro-bubbles enhancement [45]	9.2
Ratio of total electricity consumption of plant to the pumping power of desalination processes (-)	1.8
Electricity consumption (kWh/m^3)	1.8

[*] *The m^3 refers to the volume of evaporator.*
***percentage heat energy recovered from brine*

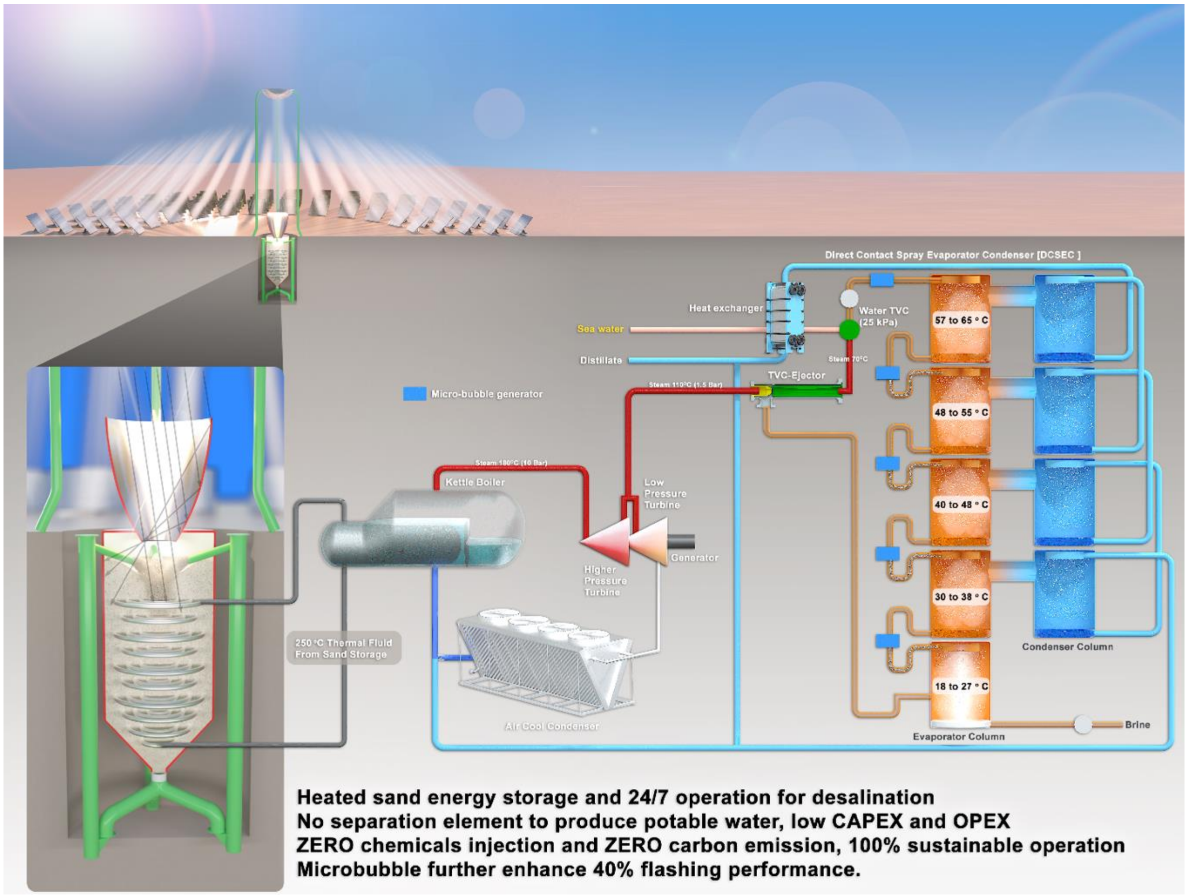
Table 6. Comparison of CAPEX, OPEX and the total unit cost for assorted desalination methods.

	SWRO	MSF	MED	DCSEC
Capital cost	0.29	0.42	0.29	0.15
Electrical	0.23	0.13	0.09	0.19
Thermal	0.00	0.33	0.24	0.08
membranes	0.03	0.00	0.00	0.00
Labor	0.10	0.08	0.08	0.08
Chemicals	0.07	0.05	0.02	0.01
Parts	0.03	0.01	0.01	0.01
Total	0.75	1.02	0.74	0.52

Table 6 presents the water production cost comparison of DCSEC with three major desalination processes. The unit water cost of DCSEC has been tabulated in same manner with the categories CAPEX and OPEX as reported by GWI for other processes. In this analysis the cost of electricity is US $0.15 per kWh. To compute for the unit cost of electricity and thermal energy input, the concept of common or standard primary energy (SPE) platform [46-50] is utilized where electrical and thermal energies has been converted into primary energy using appropriate conversion factors developed in mentioned literature (1 kWh_{elec} and 1 $kWh_{thermal}$ would consumed 1.8 and 0.1 kWh_{spe} respectively). It can be clearly seen that DESEC has lowest water production cost, $0.52/$m^3$, as compared to other processes. One can argue that DCSEC energy should be same as MED or MSF. It is correct if DCSEC system is without heat recovery and microbubble enhancement. We demonstrated that heat recovery and microbubble injection can improve performance substantially and hence reduce energy consumption.

6. Future process design concept

Owning to the simplicity and low cost of DCSEC desalination design, we propose a hybrid solar-driven seawater desalination system that is totally green and sustainable for the future sustainability. Other than the components that produced CO_2 during manufacture, there is zero CO_2 emission from operating such a plant, as shown in Figure 9. It comprises two major parts: Firstly, a solar energy harvester using an array of heliostats with a double-reflection hyperbolic reflector and compound-parabolic-concentrator (CPC). The collected solar energy is stored underground-bed using granular sand particles when irradiated by the focused rays. To maintain a uniform temperature across the sand store, a mechanical conveyor system moves the sand from bottom to top. Heat from the storage is extracted by circulating thermal oil in tube heat exchanger and delivered to the kettle boiler producing steam to drive the steam turbines for electricity generation. Secondly, the bled steam that is used to power DCSEC system. Low-grade steam is extracted from the low-pressure turbines to drive the thermal-vapor-compressor (TVC), heating the incoming seawater feed supplied to the top-brine-temperature (TBT) stage of DCSEC. Each of the multi-stage DCSEC produces liquid flashing (vapor) by exploiting the excess enthalpy between the decreasing incoming feed and the saturation temperatures of evaporators. Further enhancement of liquid flashing is achieved by injecting micro-vapor-bubbles into the seawater feed of each stage. This hybrid design of solar-driven DCSEC is a major innovation. Solar photovoltaic thermal system can also be integrated to produce additional power for components [51-53].



Heated sand energy storage and 24/7 operation for desalination
No separation element to produce potable water, low CAPEX and OPEX
ZERO chemicals injection and ZERO carbon emission, 100% sustainable operation
Microbubble further enhance 40% flashing performance.

Figure 9. DESEC with solar thermal energy storage concept.

7. Conclusions

We have successfully demonstration a lab-scale single stage of direct-contact spray evaporation and condensation (DCSEC) with real seawater as feed and the incorporation of piece-wise technique to mimic the operation of multi-stage effect. From these test results, two major factors that significantly impact distillate production are the inlet temperature of feed spray to evaporator and the temperature differential across the evaporator and condenser chambers. It is observed that firstly, the distillate yield is nearly proportional to the temperature difference of seawater feed and saturation temperature of evaporator chamber, and secondly the minimum inception for liquid droplets flashing is about 3 K. A detailed distribution of key parameters, contributing to the OPEX and CAPEX of practical desalination and DCSEC methods, is compared with assorted desalination methods over their life span. Owing to the simplicity of DCSEC design (devoid of internals such as membrane and heat transfer tubes), the unit cost of water is the lowest amongst all practical desalination methods. From the viewpoint of sustainable solar-driven desalination, the DCSEC method is deemed the most favorable technology that could be hybridized with the solar energy harvester and boiler-steam turbines, without emitting any carbon dioxide to the ambient.

Nomenclature

GCC	Gulf Cooperation Council
DCSEC	Direct contact spray evaporation and condensation
Bcm	Billion cubic meter
GDP	Gross domestic product
MED	Multi-effect desalination
MSF	Multi-stage flash
SWRO	Seawater reverse osmosis
AD	Adsorption cycle
CAPEX	Capital expenditure
OPEX	Operational expenditure
GWI	Global water intelligence
PR	Performance ratio
TVC	Thermal vapor compressor
TBT	Top brine temperature
SPE	Standard primary energy
CRF	Capital recovery factor
CPC	Compound parabolic concentrator

Subscripts

Eva	evaporator
Con	condenser
f	feed
v	vapor
l	liter
h	hour
Ther	thermal
Elec	electrical

Acknowledgements

The authors would like to thank King Abdullah University of Science & Technology (KAUST), EPSRC project (Solar Energy Storage for Heating: A Rooftop Unit for Single Household 119995) and Northumbria University PoC grant (Solar2Water) awarded to Dr. Muhammad Wakil Shahzad.

References

1. The United Nation World Water Development Report 4 http://www.zaragoza.es/contenidos/medioambiente/onu/789-eng-ed4-v2.pdf (accessed on Dec 10 2021)
2. Abdul Ghani I. Dalvi, Radwan Al-rasheed and Mohammad A. Javeed, Studies on organic foulants in the seawater feed of reverse osmosis plants of SWCC, Desalination, 132(1-3) (2000) 217-232.
3. Muhammad Wakil Shahzad, Muhammad Burhan, Li Ang and Kim Choon Ng, Energy-water-environment nexus underpinning future desalination sustainability, Desalination 413 (2017) 52-64.
4. Waleed K.Al-Zubari, Alternative water policies for the Gulf Cooperation Council countries, Developments in Water Science 50 (2003) Pages 155-167
5. George O. Odhiambo, Water scarcity in the Arabian Peninsula and socio-economic implications, Applied Water Science 7 (2017) 2479-2492.
6. Muhammad F. Al-Rashed and Mohsen M. Sherif, Water resources in the GCC countries: an overview, Water Resources Management 14 (2000) 59-75.
7. M. A. Dawoud, Water import and transfer versus desalination in arid regions: GCC countries case study, Desalination and Water Treatment 28:1-3 (2011) 153-163
8. Waleed K Al Zubari, An overview of the GCC Unified Water Strategy, 2016-2035, WSTA-12th-Gulf-Water-Conference (https:, //wstagcc.org/WSTA-12th-Gulf-Water-Conference/waleed_zubari.pdf Accessed on Dec 9 2021)
9. IDA and GWI, IDA Worldwide Desalting Plant Inventory Report No.20 in MS Excel Format, Media Analytics Ltd., Oxford, UK, 2008.
10. Mahmoud Shatat, Mark Worall and Saffa Riffat, Opportunities for solar water desalination worldwide, Sustainable cities and society 9 (2013) 67-80.
11. Sabine Lattemann, Maria D. Kennedy, Jan C. Schippers and Gary Amy, Chapter 2 Global Desalination Situation, Sustainability Science and Engineering 2 (2010) 7-39
12. Muhammad Wakil Shahzad, Muhammad Burhan and Kim Choon Ng, Pushing Desalination Recovery to the Maximum Limit: Membrane and Thermal Processes Integration, Desalination 416 (2017) 54-64.
13. MW Shahzad, M Burhan, N Ghaffour, KC Ng, A multi evaporator desalination system operated with thermocline energy for future sustainability, Desalination 435 (2018) 268-277
14. Hassan E.S. Fath, Ashraf Sadik Hassan and Toufic Mezher, Present and future trend in the production and energy consumption of desalinated water in GCC countries, International Journal of Thermal & Environmental Engineering 5:2 (2013) 155-165.
15. Muhammad Wakil Shahzad and Kim Choon Ng, On the road to water sustainability in the Gulf, Nature Middle East, (2016), doi: 10.1038/nmiddleeast.2016.50.
16. Muhammad Wakil Shahzad, Kim Choon Ng and Kyaw Thu, A Waste Heat Driven hybrid ME+AD Cycle for Desalination, Environmental Science, Water Research Technology 2 (2016) 206-212.
17. Muhammad Wakil Shahzad, Kyaw Thu, Yong-deuk Kim and Kim Choon Ng, An Experimental Investigation on MEDAD Hybrid Desalination Cycle, Applied Energy 148 (2015) 273-281.
18. Kim Choon Ng, Kyaw Thu, Seung Jin Oh, Li Ang, Muhammad Wakil Shahzad and Azhar Bin Ismail, Recent developments in thermally-driven seawater desalination: Energy

efficiency improvement by hybridization of the MED and AD cycles, Desalination 356 (2015) 255–270.

19. Muhammad Wakil Shahzad, Kim Choon Ng, Kyaw Thu, Bidyut Baran Saha and Won Gee Chun, Multi Effect Desalination and Adsorption Desalination (MEDAD): A Hybrid Desalination Method, Applied Thermal Engineering 72 (2014) 289-297.
20. Hassan El-Banna Saad Fath, Combined multi stage flash–multi effect distillation system with brine reheat, Patent No. 2,190,299, (1998).
21. A.M. Helal, A. Al-Jafri and A. Al-Yafeai, Enhancement of existing MSF plant productivity through design modification and change of operating conditions, Desalination 307 (2012)76–86.
22. A. S. Nafeya, H. E. S. Fathb and A. A. Mabrouk, Thermoeconomic investigation of multi effect evaporation (MEE) and hybrid multi effect evaporation-multi stage flash (MEEMSF) systems, Desalination 201 (2006) 241–254.
23. A.M. Helal, A.M. El-Nashar, E. Al-Katheeri and S. Al-Malek, Optimal design of hybrid RO/MSF desalination plants Part I: Modeling and algorithms, Desalination 154 (2003) 43-66.
24. Osman A. Hamed, Ata M. Hassan, Khalid Al-Shail and Mohammed A. Farooque, Performance analysis of a trihybrid NF/RO/MSF desalination plant, Desalination and Water Treatment 1 (2009) 215–222.
25. Osman A. Hamed, Overview of Hybrid Desalintion Systems-Current Status and Future Prospects, Desalination 186 (2005) 207-214.
26. A.M. Helal, A.M. E1-Nashar, E.S. A1-Katheeri and S.A. A1-Malek, Optimal design of hybrid RO/MSF desalination plants Part III: Sensitivity analysis, Desalination 169 (2004) 43-60.
27. Ibrahim S. Al-Mutaz, Hybrid RO MSF: a practical option for nuclear desalination, International Journal of Nuclear Desalination 1 (2003) 47 – 57.
28. G. Calì, E. Fois, A. Lallai and G. Mura, Optimal design of a hybrid RO/MSF desalination system in a non-OPEC country, Desalination 228 (2008) 114-127.
29. Ennio Cardona, Salvatore Culotta and Antonio Piacentino, Energy Saving with MSF-RO Series Desalination Plants, Desalination 153 (2002) 167-171.
30. M. A. Hassan et al. A New Approach to Membrane and Thermal seawater Desalination Process Using Nanofiltration Membranes, Part 1, Desalination 118 (1998) 35-51.
31. Ibrahim S Al-Mutaz, Coupling of A nuclear Reactor to Hybrid RO/MSF Desalination Plants, Desalination 175 (2003) 259-268.
32. Ahmad Hamad, Asam Almulla and Mohamed Gadalla, Integrating hybrid systems with thermal desalination plants, Desalination 174 (2005) 171-192.
33. I.S. Al-Mutaz, M.A. Soliman and A.M. Daghthem, Optimum Design for a Hybrid Desalting Plant, Desalination 76 (1989) 177- 189.
34. Félix Alardin and Jacques Andrianne, Thermal and Membrane Process Economics: Optimized Selection for Seawater Desalination, Desalination 153 (2002) 305-311.
35. Essam El-Sayed et al. Pilot Study of MSF/RO Hybrid Systems, Desalination 120 (1998)121-128.
36. Market insight: Global Water Market in 2018 (https://www.globalwaterintel.com/products-and-services/market-research-reports/global-water-market-2018 Accessed on Dec 13 2021)

37. O. Miyatake, T. Tomimura, Y. Ide and T. Fujii, An experimental study of spray flash evaporation, Desalination 36:2 (1981) 113-128.
38. O. Miyatake, T. Tomimura, Y. Ide, M. Yuda and T. Fujii, Effect of liquid temperature on spray flash evaporation, Desalination 37:3 (1981) 351-366.
39. Yasuyuki Ikegami, Hiroshi Sasaki, Tomotsugu Gouda and Haruo Uehara, Experimental study on a spray flash desalination (influence of the direction of injection), Desalination 194:1-3 (2006) 81-89.
40. Sami Mutair and Yasuyuki Ikegami, Experimental study on flash evaporation from superheated water jets: Influencing factors and formulation of correlation, International Journal of Heat and Mass Transfer 52:23-24 (2009) 5643-5651.
41. Adel K. El-Fiqi, N. H. Ali, H. T. El-Dessouky, H. S. Fath and M. A. El-Hefni, Flash evaporation in a superheated water liquid jet, Desalination 206:1-3 (2007) 311-321.
42. Qian Chen, Muhammad Burhan, PhD; Muhammad Wakil Shahzad, PhD; Doskhan Ybyraiymkul, PhD; Faheem Hassan Akhtar, PhD; Yong Li; Kim Choon Ng, A zero liquid discharge system integrating multi-effect distillation and evaporative crystallization for desalination brine treatment, Desalination 502 (2021) 114928.
43. Chen Qian, Raid Alrowais, Muhammad Burhan, Doskhan Ybyraiymkul, Muhammad Wakil Shahzad, Li Yong, Kim Choon Ng, A self-sustainable solar desalination system using direct spray technology, Energy 205 (2020) 118037.
44. Qian Chen, Muhammad Burhan, Faheem Akhtar, Doskhan Ybyraiymkul, Muhammad Wakil Shahzad, Yong Li and Kim Choon Ng, Thermo-economic analysis and optimization of a vacuum multi-effect membrane distillation system, Desalination 483 (2020) 114413.
45. Alrowais, R. (2020). Theoretical and experimental investigation of liquid droplets flashing for low cost seawater desalination. KAUST Research Repository. https://doi.org/10.25781/KAUST-W927D
46. Kim Choon Ng, Muhammad Burhan, Qian Chen, Doskhan Ybyraiykul, Faheem Hassan Akhtar, M Kumja, Robert W. Field and Muhammad Wakil Shahzad, A Thermodynamic Platform for Evaluating the Energy Efficiency of Combined Power Generation and Desalination Plants, Nature Clean Water, 4-1 (2021) 1-10.
47. Muhammad Wakil Shahzad, Muhammad Burhan and Kim Choon Ng, A Standard Primary Energy Approach for Comparing Desalination Processes, Nature Clean Water 1 (2019) 1-7.
48. Muhammad Wakil Shahzad, Muhammad Burhan, Doskhan Ybyraimkul and Kim Choon Ng, Desalination Processes Efficiency and Future Roadmap, Entropy 21-1 (2019) 84.
49. Muhammad Wakil Shahzad, Kim Choon Ng, Muhammad Burhan, Qian Chen, Muhammad Ahmad Jamil, Nida Imtiaz and Ben Bin Xu, Demystifying Integrated Power and Desalination Processes Evaluation based on Standard Primary Energy Approach, Thermal Science and Engineering Progress 27 (2022) 101153.
50. Muhammad Wakil Shahzad, Muhammad Burhan, Hyun Soo Son, Seung Jin Oh and Kim Choon Ng, Desalination Processes Evaluation at Common Platform: A Universal Performance Ratio (UPR) Method, Applied Thermal Engineering, 134 (2018) 62–67.
51. Rajvikram Madurai Elavarasan, Vijay Mudgal, Leoponraj Selvamanohar, Kai Wang, Gan Huang, GM Shafiullah, Christos N Markides, KS Reddy, Mithulananthan Nadarajah, Pathways toward high-efficiency solar photovoltaic thermal management for electrical, thermal and combined generation applications: A critical review, Energy Conversion and Management 255 (2022) 115278.

52. Yongliang Zhao, Jian Song, Ming Liu, Yao Zhao, Andreas V Olympios, Paul Sapin, Junjie Yan, Christos N Markides, Thermo-economic assessments of pumped-thermal electricity storage systems employing sensible heat storage materials, Renewable Energy186 (2022) 431-456.
53. Gan Huang, Kai Wang, Sara Riera Curt, Benjamin Franchetti, Ioannis Pesmazoglou, Christos N Markides, On the performance of concentrating fluid-based spectral-splitting hybrid PV-thermal (PV-T) solar collectors, Renewable Energy 174 (2021) 590-605.