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Life-cycle cost analysis of adsorption cycles for desalination

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ABSTRACT

This paper presents the thermo-economic analysis of the adsorption desalination (AD) cycle that is driven by low-temperature waste heat from exhaust of industrial processes or renewable sources. The AD cycle uses an adsorbent such as the silica gel to desalt the sea or brackish water. Based on an experimental prototype AD plant, the life-cycle cost analysis of AD plants of assorted water production capacities has been simulated and these predictions are translated into unit cost of water production. Our results show that the specific energy consumption of the AD cycle is 1.38 kWh/m^3 which is the lowest ever reported. For a plant capacity of 1000 m^3/d, the AD cycle offers a unit cost of \$0.457/m^3 as compared to more than \$0.9 for the average RO plants. Besides being cost-effective, the AD cycle is also environment-friendly as it emits less CO_2 emission per m^3 generated, typically 85% less, by comparison to an RO process.

Keywords: Economic analysis; Adsorption; Desalination; CO_2 emission saving

1. Introduction

The thermodynamic limit for specific energy consumption of a desalting of saline solution to produce potable water varies from 0.78 kWh/m^3 at 1% salt concentration and 25°C [1–3]. The thermodynamic limit is the minimum unit cost at a given solution concentration that is needed to produce potable water irrespective of the physical methods employed. In 2006, Ng et al. [4] patented a low temperature and heat-driven adsorption cycle and they reported the measured performances of a prototype plant for assorted operating conditions [5,6]. Being waste heat operated, the AD cycle achieves a specific energy consumption of 1.38 kWh/m^3, which is only about twice that of the thermodynamic limit. This is, hitherto, the lowest specific energy consumption ever reported for a desalination plant. It is natural to ask: what is the unit cost of AD plant when its performance is scaled-up and compared to the commercially available methods such as multi-stage flashing (MSF), multi-effect (MED) and reverse osmosis (RO)? With only a laboratory-scale prototype available presently, the motivation of this paper is to simulate the AD plant performances at assorted water production capacities and hence, estimate the unit cost of AD plants at plant capacities that are similar to the published data from the other methods of desalination. An artist's impression of a large-scale AD plant of 3000–10000 m^3/d is shown in Fig. 1.

Potable water, which is a necessity for human consumption and industrial processes, accounts for less than 1% of all available water of the world. More than 97% of the water is found in the sea whilst 65% of the

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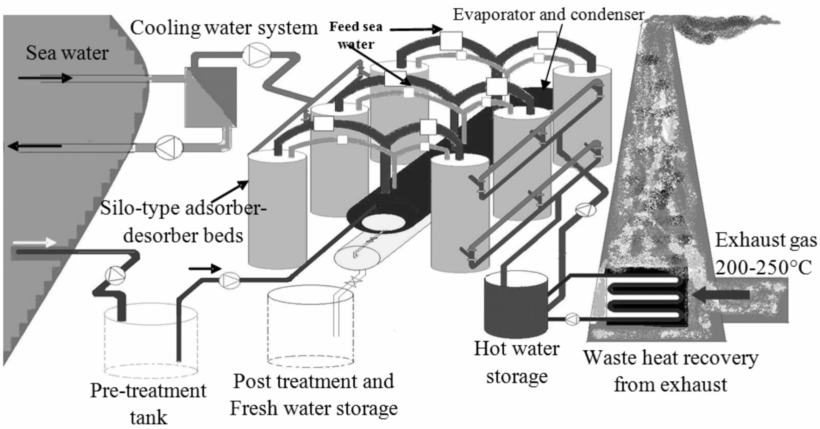

Fig. 1. An artist's impression of a large-scale adsorption desalination plant with a production capacity up to 10,000 m^3/d.

total fresh or potable water is locked in the ice-caps and underground water [7,8]. It has been reported that the factors contributing to the scarcity of fresh water are the environmental issues relating to climate change, land degradation and global warming which enhances fresh water evaporation from lakes further straining its supply. With the projected population growth and economic development rates [9], water consumption is expected to double every 20 years. At these projected rates, more people are denied accessibility to safe drinking water and basic sanitation [9]. The construction of water reservoirs in water catchment areas falls behind the need for more water in many parts of the world. Low rainfall and high demand for water in many parts of the world is further aggravated by the relentless pursuit of economic development in these countries. Seawater provides a steady feed to solving the fresh water shortage problem. Desalination process, which is the removal of salts from seawater, has been a practical solution. Thermally-activated desalination systems such as multi-stage flash (MSF) and multi effect distillation (MED), and membrane-based desalination methods such as reverse osmosis (RO), brackish water reverse osmosis (BWRO) and seawater reverse osmosis (RO) are the commercially proven desalination technologies [10–14]. More than 80% of the plants in the world are of the membrane installations whilst the remaining share is of the thermally-activated type of various capacities. However, they have equal share in terms of water production. Most of the commercially available desalination systems, hitherto, are plagued much by (i) high energy consumption of the processes, (ii) corrosion and fouling of evaporating units or membrane assemblies and (iii) high operating cost. The unit production cost of such plants was summarized succinctly by Karagiannis et al. [15].

In this paper, the authors conduct a life-cycle analysis of large-scale adsorption desalination (AD) plants that employ an adsorbent–adsorbate pair such as the silica gel–water pair. The unit costs of AD processes at these production capacities are compared with the reported costs of other desalination methods (MSF, MED, ROs) found in the literature. The key advantages of the AD plant are many. Firstly, the AD cycle extracts waste heat at low temperatures from industrial processes, exhausts of prime movers, solar renewable thermal heat, etc., typically not higher than 80°C, which is sufficient to operate. Secondly, it has almost no major moving parts which implies low maintenance in its operation. The cost projection analyzed here is based on the authors' experience in operating the prototype plant and the survey data from manufacturers for the capital and operational costs of key components in an AD plant. In addition, the cost model that can incorporate the inflation-weighted factors for the electricity prices was used. As low temperature waste heat is employed, the input energy for the AD cycle is thus "free energy" and only the parasitic electricity consumption for pumps for circulating hot and cooling water in the cycle and thus, it gives the lowest unit cost per m^3 of water. When operated at standard operating conditions, the experimental-scale prototype [16] gives a specific daily water production (SDWP) of 12–25 m^3 of potable water per day per ton of silica gel and the SDWP increases as the cooling effect reduces from the evaporator. As the paper focuses on the total cost of the AD plants only, the operational details of the AD cycles is elaborated briefly in the section below.

2. Description of the adsorption desalination (AD) plant

An adsorption (AD) desalination plant would comprise the following basic components: the evaporator, the condenser and the adsorber and desorber beds. The beds contain the silica gel which is packed into the stationary tube-finned heat exchangers, as shown schematically in Fig. 2. Low temperature heat is fed to the desorption processes to regenerate the silica gel in a batch-operated cycle. Saline or brackish water is fed intermittently into

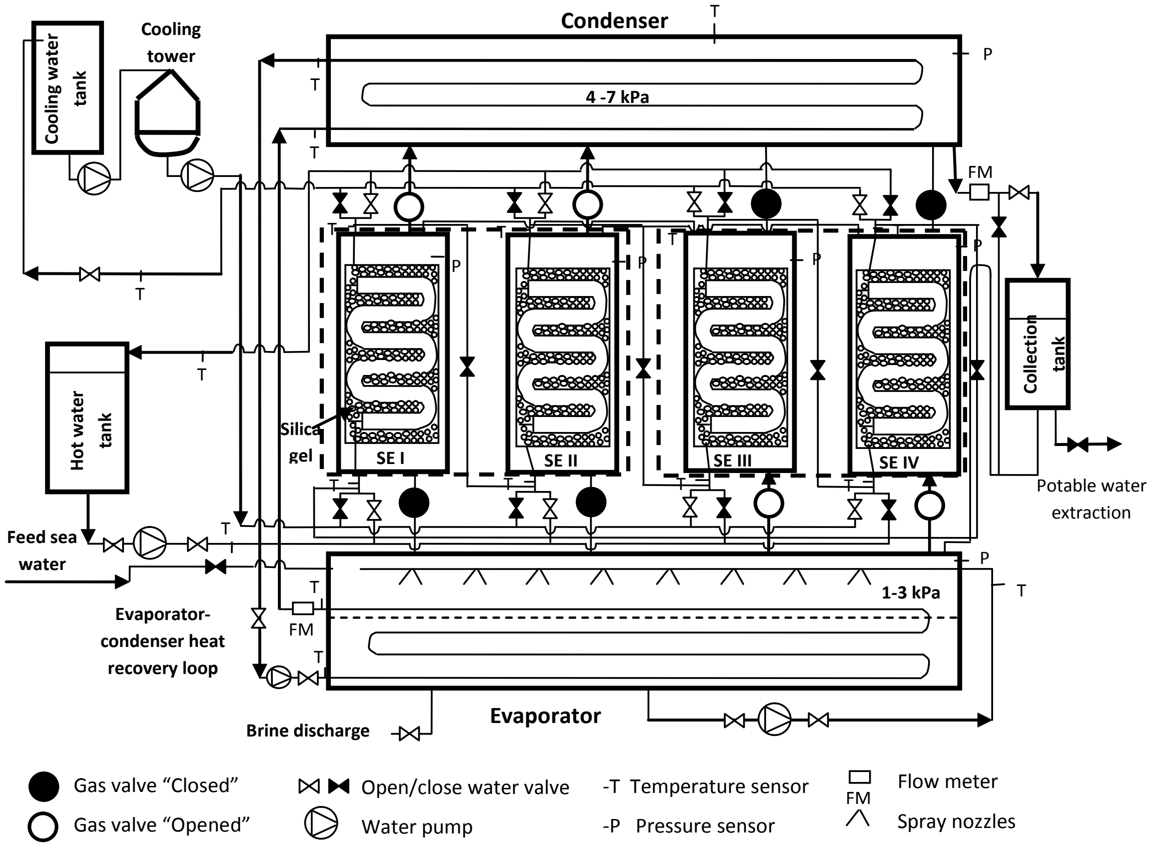

Fig. 2. The schematic diagram of the AD plant with evaporator-condenser recovery scheme.

the evaporator where desalting is achieved by evaporation at low system pressures of 1–5 kPa. The vapor is adsorbed by the silica gel (during adsorption processes). During the heat addition or regeneration, water vapor is expelled from the adsorbent and condenses in the cooling tower cooled condenser [17–21].

In principle, both useful effects can be derived from the AD cycle with only one heat input, namely, cooling at the evaporator and potable water can be extracted from the condenser. Owing to the duel useful effects, the potential of AD plants is significantly higher than that of the MED where it could only generate potable water at a similarly low temperature range. However, this paper reports only the desalination effect from the AD cycle by reducing the production of the cooling effect. The adsorbent used in the AD cycle is the silica gel that has a surface pore area of 720 m^2/g and equilibrium uptake of 0.45 kg of water vapor to the dry mass of the adsorbent [22]. The design parameters as well as the operating conditions of a typical AD cycle are summarized in Table 1. A pictorial view of the experimental pilot plant of cooling capacity of 5 R-ton is shown in Fig. 3. It has the flexibility of operating in either as a two-bed or a four-bed mode.

Fig. 4 gives the temporal temperature profiles of the batched-operated adsorber, the desorber, as well as the evaporator and the condenser of the experimental AD plant. The AD plant operates optimally at 360 s half-cycle time and the switching time is kept at 20 s while the hot water at 85°C is utilized to drive the plant. Owing to the direct heat recovery circuit between the condenser and evaporator, the temperatures in the condenser and evaporator are both raised to 40–41°C and 47–48°C, respectively. The higher evaporator temperature (hence the saturation pressure) has a pressurization effect on the uptake of vapor on the silica gel during its adsorption process.

Table 1
Design parameters and operation conditions of AD plant

Adsorbent	Type RD silica gel
Number of adsorber	4
Mass of adsorbent/adsorber, kg/bed	36
Cycle time, s	720–1200
Switching time, s	20–40
Hot water inlet temperature, °C	85
Cooling water temperature, °C	30

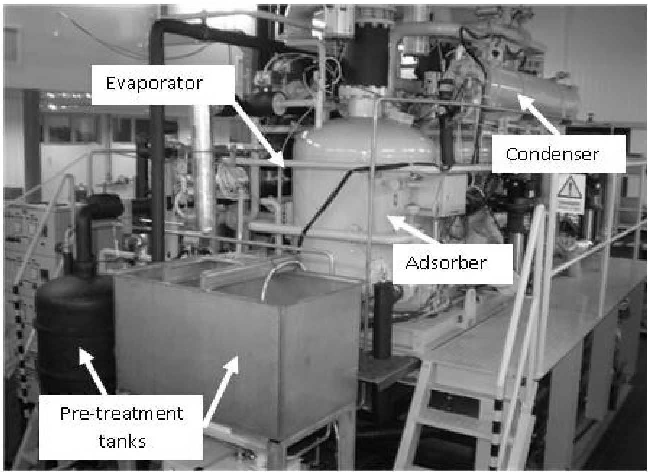

Fig. 3. Pictorial view of the AD plant.

Water production of the AD plant over the same cyclic intervals is shown in Fig. 5. For 144 kg of silica gel in the beds, the specific daily water production (SDWP) of the experimental plant can be translated to an average of 25 m^3 of potable water per ton of silica gel per day, operating at standard rating conditions: waste heat is supplied at 80°C and cooling tower water is supplied at 30°C. The recovery ratio of the AD cycle is about 65–75% and this is achievable since the vapor uptake is controlled by the adsorption phenomenon of the adsorbent and there is no crystallization found on the tube surfaces. A slight decrease in the SDWP is, however, observed at higher salt concentration, caused by the vapor pressure depression effect [23,24].

It is noted that only waste heat at 80°C (if it is not recovered would be purged in the process) is supplied to the AD cycle and is deemed free. The electricity used to operate the AD cycle will be considered for cost analysis. The electricity or operational cost advantage of an AD cycle over the other commercially available methods is shown in Table 2 where energy costs from both thermal and electricity are considered.

From the comparison of energy costs, the AD process offers the lowest specific energy consumption for the production of potable water, at 1.38 kWh/m^3. This value is about twice that of the thermodynamic limit. The recovered waste heat from industrial processes or exhaust is deemed free and only parasitic electricity is consumed for the plant's operation.

3. Total cost

The total costs of a desalination plant comprise capital, operational and replacement costs of key components such as heat exchangers, membranes, etc. Depending on the desalination methodology and water production capacity, the plant life would affect the annualized capital cost via the amortization period (n) and the interest rate (i) through a capital recovery factor (CRF), i.e., the product between the initial investment and the CRF. The operational cost would comprise the contributions from

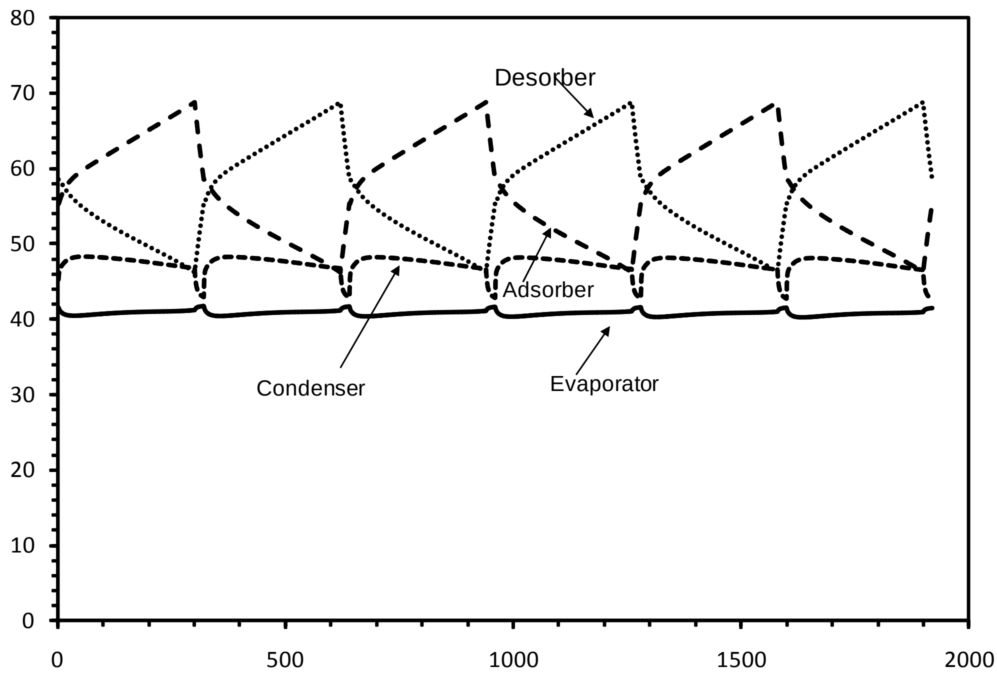

Fig. 4. Cyclic steady-state temperatures in the adsorber, desorber, condenser and evaporator of AD plant.

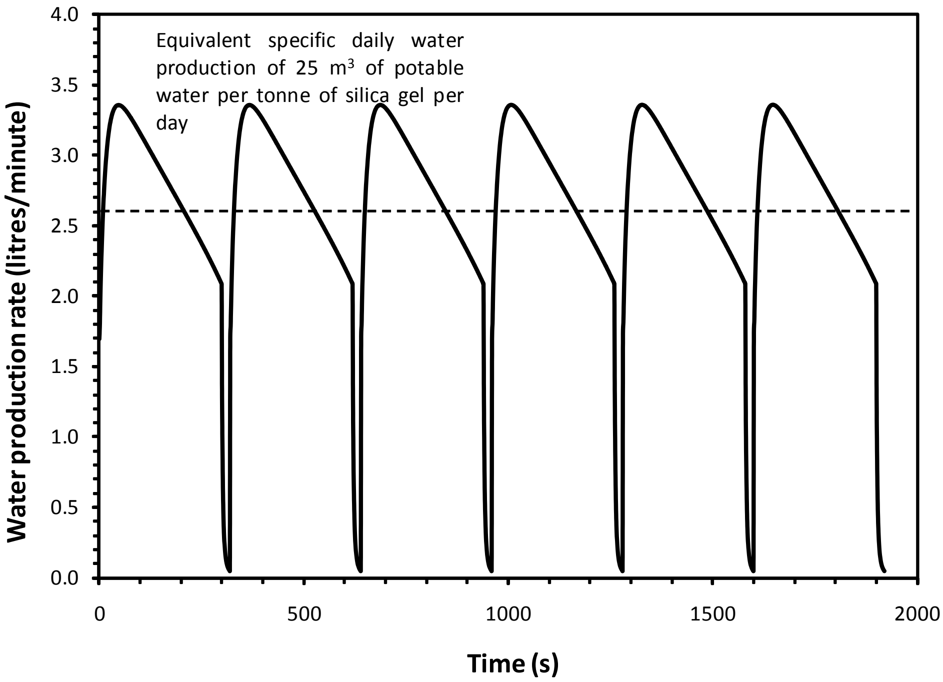

Fig. 5. Water production rates from the condenser during the batch-operation of the AD plant.

Table 2
Energy cost of different desalination methods

Method of desalination	Thermal energy consumed (kWh/m^3) (A)	Electric energy consumed (kWh/m^3) (B)	Energy cost of water, US\$/m^3 = [5×(A×3.6)/(1055×η_b) + B×0.133]
Multi-stage flash (MSF)	19.4	5.2	1.11
Multi-effect distillation (MED)	16.4	3.8	0.86
Vapor compression (VC)	—	11.1	1.48
Reverse osmosis (RO) – single pass	—	8.2	1.09
Reverse osmosis (RO) – double pass	—	9.0	1.20
Advanced AD (high grade water)	Free energy from waste heat	1.38	0.18

All data is extracted from Seawater Desalination in California, California coastal commission Chapter 1: Energy Use section, http://www.coastal.ca.gov/index.html. The conversion units of 1 AF = 1345 m^3, 1 million BTU (1.055 GJ) of natural gas costs US\$5 (adopted from Singapore's natural gas prices quoted in 2005) and the electricity rate US\$ 0.13/kWh. The efficiency of boiler, η_b, is 80%.)

fuel and electricity rates, maintenance and replacement, pumping requirements, chemical treatment of feed and output water. In reality, all operational costs can be subjected to the inflation effect or rates (j), arising from primary fuel, electricity price fluctuations, etc. Such increases over a period of time into the future could be incorporated by using the inflation weighted factor, IWF = CRF(i,n)/CRF(i′,n). A life cycle approach is adopted here for the calculation of the unit cost of desalination, i.e.

$$A\left(\$/\mathrm{m}^3\right)=\left[\sum_{k=1}^{m} C_{\mathrm{capital}}\left(\mathrm{CRF}\,(i,n)\right)_k\right] + \left[\sum_{l=1}^{p} C_{\mathrm{operational}}\left(\frac{\mathrm{CFR}\,(i,n)}{\mathrm{CRF}\,(i',n)}\right)_l\right] \quad (1)$$

where A is the unit cost of desalination on a volumetric basis, n is the number of items of capital investment, p is the number of items related to operational cost. With

Table 3
Equations used to calculate the capital and operational costs of an AD plant

Item	Equation
V_L, volume of water produced by plant over the life span (y)	V_L = (SDWP)(M_{sg})(365)(N), where SDWP is the specific daily water production rate in m³/tonne of adsorbent, M_{sg} = mass of adsorbent, N = lifespan in years.
Capital recovery factor (CRF(i,n))	$\mathrm{CRF}(i,n)=\dfrac{i(i+1)^n}{(i+1)^n-1}$
Inflation weighted factor with inflation rate j, (IWF)	$\dfrac{\mathrm{CRF}(i,n)}{\mathrm{CRF}(i^{'},n)}$ where $i^{'}=\dfrac{i-j}{1+j}$
Capital cost per unit volume	$C_{\text{capital}}=\dfrac{D_{\text{capital}}}{V_L}$
Pumping power	$W_{\text{pumps}}(\mathrm{kW})=\sum_j \dfrac{\Delta P_j(\mathrm{kPa})\times V_{\text{pump},j}\left(\mathrm{m}^3/\mathrm{s}\right)}{\eta_j}$ where V_{pump} is the volumetric flow rate and η is the typical pump efficiency, j is the number of pumps.
Pumping cost per unit volume	$C_{\text{electrical}}=\dfrac{E_{\text{pumps}}\times \text{yearly operating hour}}{V_L}$ where E_{pumps} (\$/h) = W_{pumps} (kW) × Electricity rate (\$/lWh)
Maintenance cost per unit volume	$C_{\text{maintenace}}=(D_{\text{capital}}\times\beta)/V_L$ where β = 4.63% is in percentage of the unit capital cost.
Manpower cost per unit volume	$C_{\text{manpower}}=(D_{\text{capital}}\times\alpha)/V_L$ where α = 8.11% is in percentage of the unit capital cost

Eq. (1), the unit production cost of AD plants of varying water production capacities is realistically estimated and Table 3 depicts all the equations used for the capital and operational costs of an AD plant over the plant life.

For a fair comparison, we have selected reasonably large RO desalination plants [25,26] of 1000 m³/d where the assumed plant life is 30 years; an interest rate is 5%, and here the inflation rate effect is omitted in order to reflect the unit production cost in present value. Table 4 tabulates the key parameters used for the cost calculation. The maintenance cost of the AD plant is b = 4.63% of direct capital cost. The feed seawater is pre-treated with micro air bubbles to remove the suspended solids by flocculation and almost no chemicals are used, reducing the pre-treatment cost significantly. The manpower cost consists of the salary of operators in the plant and it is dependent on the locality of the plant. For survey, it is assumed 8.11% of the direct capital cost. The thermal energy input to the AD plant is deemed free as it is extracted from waste heat or obtained from the solar energy. However, the cost of the thermal energy extraction equipments such as heat exchangers is included in estimation of the capital cost.

Table 5 summarizes the contributions from all costs (capital and operational) in the life-cycle analysis of the adsorption desalination cycle and the RO plants [25,26] at a capacity of 1000 m³/d. The electricity rate is adjusted with the previous rates published by the utility companies in Singapore over the past decade.

Based on these assumptions, the unit cost for AD plants of water production capacities from a few tens to a thousand m³/d are computed and their predicted unit costs are depicted in Fig. 6. At 1000 m³/d, the lowest unit cost of AD plant is \$0.457 — one of the lowest unit costs ever reported. The operation cost is almost constant with respect to the output capacity of AD plants whilst the capital cost decreases exponentially due to the scaling of the plant sizes. At this capacity, the relative contributions from the capital and operation are roughly equal at 50% but at lower capacities, however, the contribution from capital cost increases significantly. When compared with the published unit cost of a RO plant (1000 m³/d), the unit cost of RO plant is reported to be more than twice that of the AD plant at \$0.944/m³. The major cost contributions of RO operation are the higher operational costs such as the electricity cost, chemical, maintenance and the membrane costs. It is noted that in almost all reports of RO plants, the replacement cost of membranes has been left vague or not clearly reported. The replacement period of membranes is known to vary from 12 months to 5 years, depending on the quality of water feeding through. In [26], Cothers of a RO plant is defined as “the costs attributed to factors not discussed here.” This uncertainty has resulted in the

Table 4
Cost parameters of the AD plant and the reference RO plant [25,26] with adjusted Singapore electricity rate and the interest rate

	AD plant	Reference RO plant [25]	Reference RO plant [26]
Water production capacity, m^3/d	1000	1000	1000
Plant life *n*, y	30	30	30
Interest rate *i*, %	5	5	5
Electricity rate, US$/kWh	0.133	0.133	0.133

Table 5
Contributions to the total costs for AD and RO plants at 1000 m^3/d

Unit cost factors	AD plant			RO plant [25]			RO plant [26]		
	($/$m^3$)	(% of total)		($/$m^3$)	(% of total)		($/$m^3$)	(% of total)	
$C_{capital}$	0.259	56.7		0.215	22.8		0.127	15.9	
$C_{electrical}$	0.164	35.9	43.3	0.260	27.5	77.2	0.260	32.6	84.1
$C_{manpower}$	0.021	4.6		0.050	5.3		0.021	2.6	
$C_{pre\text{-}treatment}$	0.001	0.2		0.035	3.7		0.0035	0.4	
$C_{chemical}$	—	—		0.035	3.7		0.1	12.5	
$C_{maintenance}$	0.012	2.6		0.061	6.5		0.039	4.9	
Cmembrane	—	—		0.060	6.4		0.02	2.5	
C_{others}	—	—		0.228	24.1		0.228	28.6	
Total cost = $\sum_i C\left(\$/\mathrm{m}^3\right)$	0.457	100		0.944	100		0.799	100	

Here, the parameters $C_{pre\text{-}treatment}$, $C_{chemical}$, $C_{membrane}$ and C_{others} are the pre-treatment cost, chemical cost, membrane replacement cost and cost per unit volume of the potable water, respectively.

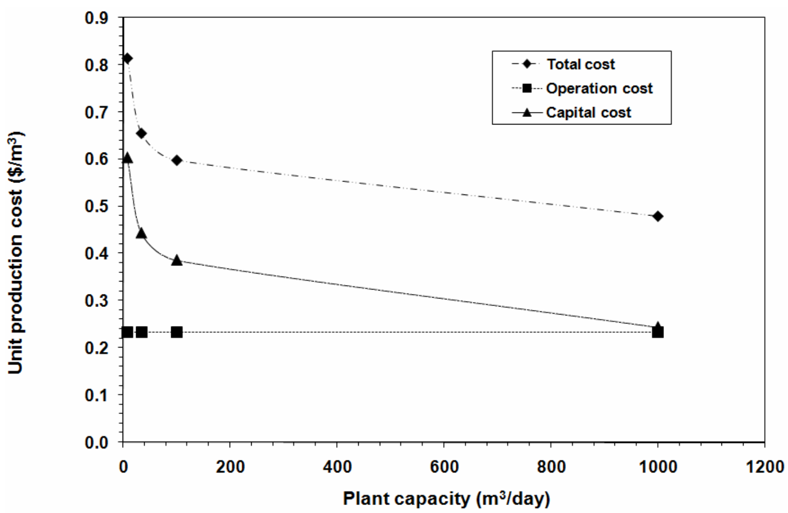

Fig. 6. Potable water production cost by AD cycle with different plant capacities.

incorporation of a factor of 0.228 (as quoted in [26]) and it is depicted as "others" in the last row of Table 5. This may account up to more than 20% of the unit cost of water.

The sensitivity analysis on the unit production cost by the AD plant with the capacity of 1000 m^3/d has been conducted for two scenarios. In the first scenario, the sensitivity in the unit cost with changes in the interest rate is evaluated. The uncertainty contributed by the electricity

Table 6
Sensitivity analysis on the unit production cost of water by the AD plant with the interest rate and the electricity rate

Interest rate (%)	% change in unit production cost	Electricity rate (US$/kWh)	% change in unit production cost
4.0	–6.3	0.100	–9.0
4.5	–3.2	0.120	–3.6
5.0	0.0	0.133	0.0
5.5	3.3	0.147	3.6
6.0	6.6	0.160	7.2

rate has been investigated in the second scenario. Table 6 summarizes the percentage change in the production cost with interest rate and the electricity rate.

Based on the cost data available in the literature, Fig. 7 compares the unit potable water production costs by conventional desalination methods such as MSF, MED, BWRO and SWRO, compared with AD process. Despite the higher capital cost, the AD cycle still offer the lowest production costs for the sea water desalination process for the following reasons: Firstly, the AD cycle is operated by waste or renewable heat which is available free and parasitic electricity consumption in the plant is the lowest. Secondly, the AD plant has almost no major moving parts with desalting occurring at low temperatures, minimizing its maintenance cost to the lowest possible. Most importantly, the AD cycle requires no chemicals for cleaning, both at the pre and post treatment of water. Such key advantages and coupled with the robust processes in the cycle; the AD plant is believed to be the most efficient desalination process in the world.

The environment-friendly aspect of the AD plant is demonstrated here by comparing the amount of CO_2 emission. The primary fuel used in all cases is assumed to be natural gas where the emission rate of CO_2 is taken as 64.2 tonne per TJ [27]. Based on the thermal and electricity consumption of Table 2, the corresponding CO_2 emission of the conventional desalination processes of MSF, MED and RO plants could also be computed. An established procedure of CO_2 emission is assumed and details of the approved method is outlined in the Appendix. In Table 7, the baseline emission for thermal, electricity consumption of the conventional methods of desalination are compared

Table 7
CO_2 emissions by the AD plant as compared to the conventional desalination methods for a water production capacity of 1000 m^3/d

Method	$TB_{th,y}$ (t CO_2/y)	$EB_{elec,y}$ (t CO_2/y)	BE_y (t CO_2/y)	ER_y (t CO_2/y)
MSF	1637	875	2512	2305
MED	1383	640	2023	1816
RO	0	1380	1380	1173
AD	0	207	207	—

$TB_{th,y}$ is the annual CO_2 emission from the burning of natural gas, $EB_{elec,y}$ is the emission from the generation of electricity consumed, BE_y is the baseline annual CO_2 emission and ER_y is the annual CO_2 emission reduction by the AD plant for the same amount of desalting

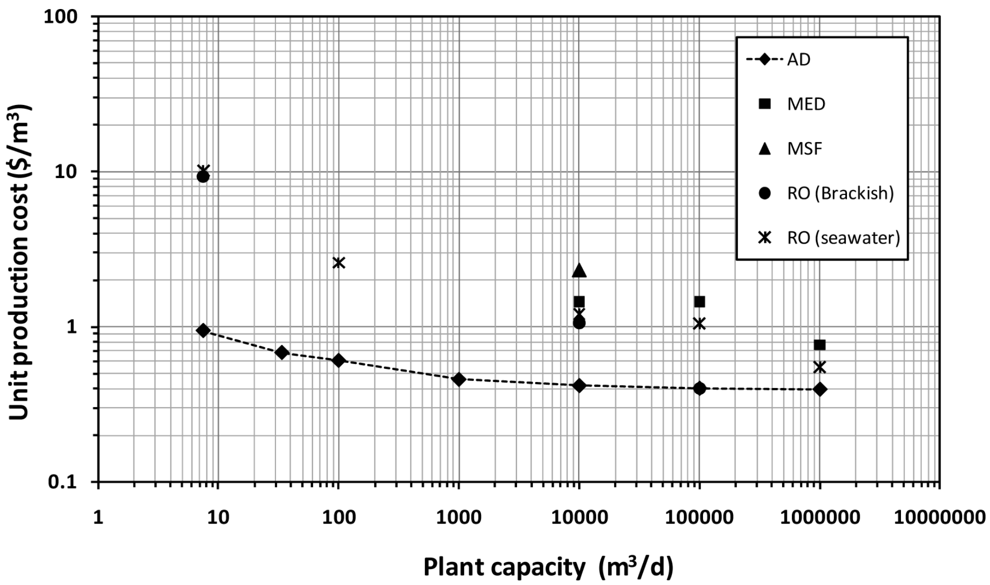

Fig. 7. Unit production cost of desalination from different methods and plant capacities.

to the emission obtained by the AD plant at the same water production capacity, and the last column indicates the respective CO_2 savings.

4. Conclusion

The thermo-economic study of the adsorption desalination (AD) process has been analyzed using a life-cycle approach. The specific energy cost of the AD plant is found to be 1.38 kWh/m^3 — the lowest energy usage ever reported for any desalination method. For a large AD plant of 1000 m^3/d or higher, the total life-cycle cost gives a unit production cost of \$0.457/m^3 as compared to \$0.944/m^3 of an equivalent RO plant. The AD cycle is distinctly a superior method for desalination when a low temperature waste heat source is available. Not only are the AD plants cost-effective, it could produce high-grade water with almost no chemicals for the pre and post-treatment of seawater. Owing to waste heat recovery, the AD processes emit lesser CO_2 by comparison to an equivalent RO plant: savings of at least 1172 tonnes of CO_2/y or 3 kg of CO_2 per m^3 of water can be realized. Hence, the AD cycle is a promising and practical solution for quenching the global thirst by desalination as well as an excellent method of reducing the global warming.

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Appendix

Baseline calculation for the emission of CO_2

The baseline emissions of CO_2 by a desalination process can be estimated as the sum of CO_2 emissions from thermal energy and electrical energy utilization. For the thermally activated systems, the emission of CO_2 emanates from the energy consumed in evaporating the seawater as well as the electricity consumption for the moving the coolant or heat sources. On the other hand, the membrane desalination processes would consume electricity for pushing the saline solution and the permeate. The following equations provide the method of calculation for the baseline emission for a desalination process.

$$BE_{\mathrm{y}}(\mathrm{t\ CO_2/y}) = TB_{\mathrm{th,y}} + EB_{\mathrm{elec,y}} \quad \text{(A1)}$$

where BE_y is the baseline annual CO_2 emission, $EB_{elec,y}$ is the emission from the generation of electricity consumed and $TB_{th,y}$ is the annual CO_2 emission from the burning of natural gas for desalting. $TB_{th,y}$ can be calculated using the following equation:

$$TB_{\mathrm{th,y}} = Q_{\mathrm{elec,y}}(\mathrm{MJ/y}) \times EF_{\mathrm{gas}}(\mathrm{t\ CO_2/MJ}) \quad \text{(A2)}$$

where $Q_{elec,y}$ (MJ/y) is the annual thermal energy required for the desalination of typical amount of potable water and EF_{gas} (t CO_2/MJ) is the emission factor for the burning of natural gas. The value of EF_{gas} is taken as 6.42×10^{-5} t CO_2/MJ [28].

The emission from the electricity consumed in desalination process, $EB_{elec,y}$, is calculated as

$$EB_{\mathrm{elec,y}} = EG_{\mathrm{y}}(\mathrm{MWh/y}) \times CEF_{\mathrm{elec}}(\mathrm{t\ CO_2/MWh}) \quad \text{(A3)}$$

where EG_y is the amount of electricity generated by the power plant and CEF_{elec} is the CO_2 emission factor for the generation of the electricity and its value is taken as 0.4612 [29,30].

The CO_2 emission reduction by AD process is given by:

$$ER_{\mathrm{y}}(\mathrm{t\ CO_2/y}) = BE_{\mathrm{y}} - ADE_{\mathrm{y}} \quad \text{(A4)}$$

Here, ER_y and ADE_y are the annual CO_2 emission reduction and the annual CO_2 emission by the AD plant. The following expressions are used to estimate the CO_2 emission by the AD plant.

$$ADE_{\mathrm{y}}(\mathrm{t\ CO_2/y}) = EB_{\mathrm{elec,y}} \quad \text{(A5)}$$

And the units are similar to tonnes of CO_2/y.