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An exergy approach to efficiency evaluation of desalination

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This paper presents an evaluation process efficiency based on the consumption of primary energy for all types of practical desalination methods available hitherto. The conventional performance ratio has, thus far, been defined with respect to the consumption of derived energy, such as the electricity or steam, which are susceptible to the conversion losses of power plants and boilers that burned the input primary fuels. As derived energies are usually expressed by the units, either kWh or Joules, these units cannot differentiate the grade of energy supplied to the processes accurately. In this paper, the specific energy consumption is revisited for the efficacy of all large-scale desalination plants. In today's combined production of electricity and desalinated water, accomplished with advanced cogeneration concept, the input exergy of fuels is utilized optimally and efficiently in a temperature cascaded manner. By discerning the exergy destruction successively in the turbines and desalination processes, the relative contribution of primary energy to the processes can be accurately apportioned to the input primary energy. Although efficiency is not a law of thermodynamics, however, a common platform for expressing the figures of merit explicit to the efficacy of desalination processes can be developed meaningfully that has the thermodynamic rigor up to the ideal or thermodynamic limit of seawater desalination for all scientists and engineers to aspire to. *Published by AIP Publishing.* [<http://dx.doi.org/10.1063/1.4982628>]

Water, energy, and environment are inextricably linked when desalting the seawater. As more potable water is produced, more energy is consumed and concomitantly more CO₂ gases are emitted. In the water-stressed countries of the world, the availability of these resources at affordable prices strengthened the growth rate of their economy. Water is pervasive to all energy production sectors, such as fossil fuel processing, power generation, and irrigation of feedstock crops for biofuels. The practical processes of seawater desalination available hitherto, namely, the seawater membrane-based reverse osmosis (SWRO), thermally driven multi-stage flashing (MSF), and the multi-effect distillation (MED) methods,^{1–6} are known to be energy intensive when compared to the ideal or thermodynamic limit (TL) of desalination.^{7–10} The TL is an *ideal concept* of desalination with no entropy generation, and depending on the source of seawater, its salinity may vary from 3.0% to 4.5% by weight. For the Middle East and North African (MENA) countries, the specific energy consumption is calculated to be in the range of 0.7 to 0.85 kWh/m³, and the TL that has a minimum work of nominal seawater at 25 °C is about 0.78 kWh_{pe}/m³.^{11–20}

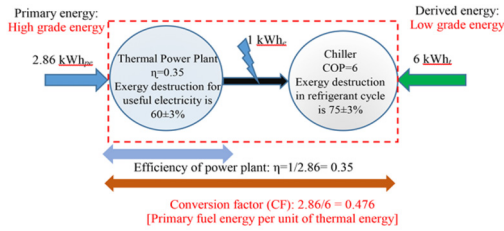
The existing desalination plants efficiency, performance ratio (PR), is defined as a ratio of the equivalent evaporative energy of distillate to the energy input, as presented in Equation (1). The conventional PR is based on derived energies such as electricity and thermal

$$PR = \frac{h_{fg}}{3.6 \left\{ \left(\frac{kWh_{elec}}{m^3} \right) + \left(\frac{kWh_{ther}}{m^3} \right) \right\}}, \quad (1)$$

where h_{fg} is the latent heat of evaporation of potable water in kJ/kg, kWh_{elec}/m^3 and kWh_{ther}/m^3 are the derived energies,

while the constant 3.6 is the unit conversion factor. This conventional PR may appear reasonable in industry for comparing the desalination processes, but it has inherently two weaknesses: First, the electricity by desalination processes is susceptible to the overall power plant efficiency, 35%–50%. Second, the units of derived thermal energy, kWh, are unable to differentiate the quality of energy consumed by the cascaded processes. Considering all derived energies, as thermodynamically the same in PR calculations, it can be deceptive in comparing assorted desalination methods. This misconception is commonly observed in cogeneration plants where two or more useful effects are produced simultaneously where different grades of derived energies are measured as kWh.^{21–29} As today's desalination plants are aptly designed with the concept of cogeneration to judiciously distribute the exergy of input primary fuel between the combined cycle gas turbines (CCGTs) and steam turbines and the thermally driven multi-effect desalination (MED) processes, it is crucial to distinguish the relative exergy destruction incurred by each process. Thus, the measured derived energy of a process can then be rightfully apportioned with respect to the input primary energy.

The omission of the grade of energy consumed by the desalination processes can be attributed historically to the primitive design arrangements of a single-purpose built plant, where neither the energy nor exergy analysis makes any difference to the primary energy apportionment. For example, the electricity is generated from a simple power plant or the steam is produced by a burning fuel directly in a boiler: A one-to-one relationship between the input and the useful output negates the need for an accurate exergy approach. Another example is a chiller for providing the



	Energy	CF_Energy	Exergy	CF_Exergy
Power plant	0.47	1/0.35	0.60±0.03	0.61
Chiller	6	1/6	0.75±0.03	0.77
Net conversion factor		2.85 x 0.167 = 0.47		0.61 x 0.77 = 0.47

FIG. 1. An example of a single useful-effect output power plant for cooling application. It is observed that the same conversion factor of 0.47 can be attained from either the enthalpy or exergy methods.

cooling effect, as shown in Figure 1, where it delineates the detailed energy and exergy flows by considering a unit amount of electricity produced from a dedicated power plant.^{30,31} The electricity is then used to operate a refrigerant-based chiller of nominal Coefficient of Performance (COP) for useful cooling. Both enthalpy and exergy analyses yielded the same overall conversion factor (CF) of about 47%.

It is emphasized that when the figure of merit, PR, is applied to desalination processes within a cogeneration-type CCGT power plant, the energy consumption should be expressed in terms of the primary energy, providing a level platform for the cross comparison of assorted desalination methods. To mark the distinction between the conventional PR and the primary energy based PR, the latter is termed universal PR or UPR in short. The accurate conversion of derived energy to primary energy consumption is the key for having an equitable platform for comparing all desalination methods and the fuel cost apportionment. Furthermore, it subsumes all associated conversion losses and the exergy destruction, and hence, an exergetic analysis is the most appropriate approach to calculate these conversion factors. Besides the UPR, an alternative definition for the efficacy of desalination is also given, that is, a ratio of potable water product to the primary energy input derived from the desalination process or plant that encompasses all losses incurred by all desalinating processes or cycles.

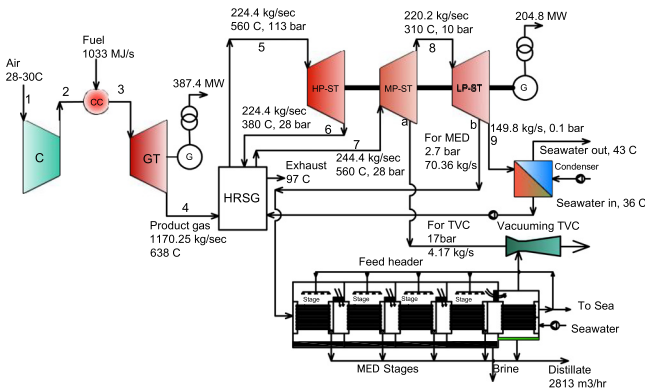


FIG. 2. An example of a cogeneration plant with a nominal electricity and water production of 594 MW and 2813 m³/h, respectively, and the processes are operated in a temperature-cascade manner.

TABLE I. The thermodynamic states at inlet and outlet streams of the major components (denoted by the *state* points) in the cogeneration plant of Figure 2.

State points of Figure 2	\dot{m} (kg/s)	T (K)	P (bar)	h (kJ/kg)	s (kJ/kg K)
1	974.95	305	1	305.64	1.718
2	974.95	592	8	599.3	2.391
3	1170.25	1470	8	1559.1	3.42
4	1170.25	911	1.2	945	2.86
5	244.40	833	113	3512.07	6.7
6	244.40	653	28	3343	7.08
7	244.40	833	28	3590	7.41
a	4.17	673	17	3250	7.2
8	240.23	583	10	3240	7.35
b	70.36	473	2.7	2865	7.4
Input to 2nd LP-ST	169.87	473	2.7	2765	7.4
9	169.87	319	0.1	2690	8.165

In today’s optimally designed cogeneration plants that produce two or more useful output, the thermodynamic-rigorous exergy approach has to be considered for the differentiation of the quality or grade of energy use by the temperature-cascaded processes.^{32–36} The exergy destruction analysis accurately apportions the amount of primary energy consumed by the major components of the plant. This is demonstrated by considering a cogeneration of power (594 MW electricity from gas and steam turbines) and desalination (2813 m³/h), as shown schematically in Figure 2. The major components are arranged synergistically where the gas turbine (GT) generators are operated with high exergy gases, while both the steam turbines and the thermally driven desalination processes are powered by the recovered exergy from the GT exhaust gases. Table I outlines the inlet and outlet pressures, temperatures, and flow rates, while the respective enthalpy and entropy can be readily computed to provide the exergy destruction analyses across all key components. The distribution of exergy destruction of combined-cycle gas turbines (CCGTs) is 75% and the heat recovery steam generator (HRSG) has the remaining 25%. The latter exergy is converted into steam which operates the multi-stages steam turbines (ST), the steam condenser, and the multi-effect distillation (MED).

Approximately 20 ± 1.5% of the available exergy is converted into steam of high pressure and temperature, which is then supplied to the steam turbines for further power production and the thermally driven MED desalination processes.

TABLE II. Primary fuel proportion utilization by cogeneration components based on exergy and enthalpy analysis.

Process	Conventional energy method (%)	Proposed exergy method (%)	Over/lower charging (%)
Gas turbines (GT including combustor, air compressor)	43.67	73.17	-40.32
Heat recovery steam generator (HRSG)	56.33	26.83	
Steam turbines (HP, MP and LP turbines)	39.58	23.11	71.2
MED desalination	16.75	3.72	350.8

TABLE III. The average conversion factors for derived energy (such as electricity and thermal input) to primary energy requirement of MSF and MED processes.

Type of derived energy	Conversion factors
Electricity (φ_1)	1/0.47
Thermal energy input at a supplied temperature	...
MED at a TBT = 60 °C ($\varphi_2^{(TBT=60C)}$)	0.038
MSF at a TBT = 110 °C ($\varphi_2^{(TBT=110C)}$)	0.054

Only less than $2 \pm 0.5\%$ of the available exergy is purged to the ambient as exhaust of combustion products. Despite the lower grade of the steam from the HRSG, the multi-stage steam turbines seem to be efficient in generating 40% of the total electricity production. Only a small fraction of low-grade steam from the last or low pressure stage of steam turbines is bled-off to operate the MED for seawater desalination. Based on the thermodynamic states of the key components of cogeneration design, the exergy destruction calculations accurately apportioned the available work of primary energy input to the derived energies, determining the conversion factors (φ_i) between the electricity, thermal energy, etc., and the exergy input. Table II summarizes the

TABLE IV. The conversion of derived energy to primary energy using published data found in literature.⁴⁶⁻⁵⁷

Types of desalination method.	Derived energy		Conversion to primary energy (kWh _{pe} /m ³)				
	Electricity (kWh _{elec} /m ³)	Thermal (kWh _{ther} /m ³)	Electricity (φ_1)	Thermal (φ_2) inclusive of weighted condenser losses	Total primary energy (kWh _{pe} /m ³)	Performance ratio (UPR)	% of thermodynamic limit (TL)
SWRO(83) (Ref. 46)	7.58	0	16.17	0.00	16.17	39.96	4.83
SWRO(86a) (Ref. 46)	6.32	0	13.48	0.00	13.48	47.93	5.79
SWRO(86b) (Ref. 57)	7.93	0	16.92	0.00	16.92	38.20	4.61
MED(89) (Ref. 47)	5	65.93	10.67	1.57	12.24	52.75	6.37
MSF(89) (Ref. 48)	4.3	80.76	9.17	4.36	13.53	47.74	5.77
SWRO(89) (Ref. 57)	6.11	0	13.03	0.00	13.03	49.57	5.99
MED(90) (Ref. 49)	2.35	104	5.01	2.5	7.50	86.09	10.4
SWRO(90) (Ref. 49)	5.8	0	12.37	0.00	12.37	52.22	6.31
SWRO(93) (Ref. 46)	5.4	0	11.52	0.00	11.52	56.09	6.77
MED(94) (Ref. 47)	2.9	68.74	6.17	1.65	7.82	82.46	9.96
MSF(97) (Ref. 48)	4.2	80.76	8.94	4.04	12.98	48.51	5.86
SWRO(97) (Ref. 46)	5.02	0	10.71	0.00	10.71	60.34	7.29
SWRO(98a) (Ref. 56)	5.85	0	12.48	0.00	12.48	51.78	6.25
SWRO(98b) (Ref. 57)	5.56	0	11.86	0.00	11.86	54.48	6.58
SWRO(99) (Ref. 46)	4.51	0	9.62	0.00	9.62	67.16	8.11
SWRO(00) (Ref. 57)	7.42	0	15.83	0.00	15.83	40.82	4.93
MED(01) (Ref. 50)	2.3	71.67	4.89	1.72	6.61	97.71	11.78
MSF(01a) (Ref. 48)	4.2	99.4	8.93	4.97	14.32	45.10	5.45
MSF(01b) (Ref. 50)	3.6	80.56	7.66	4.03	12.00	53.71	6.49
MSF(01c) (Ref. 48)	3.5	80.76	7.45	4.04	11.50	54.63	6.60
SWRO(01a) (Ref. 50)	4.2	0	8.96	0.00	8.96	72.12	8.71
SWRO(01b) (Ref. 46)	4.43	0	9.45	0.00	9.45	68.37	8.26
SWRO(03) (Ref. 46)	4.3	0	9.17	0.00	9.17	70.44	8.51
MED(04) (Ref. 51)	3.28	76.1	7.00	1.83	8.83	73.23	8.84
MSF(04) (Ref. 51)	3.98	76.1	8.49	3.81	12.30	51.28	6.19
SWRO(04) (Ref. 51)	4.9	0	10.45	0.00	10.45	61.82	7.47
SWRO(05) (Ref. 46)	3.97	0	8.47	0.00	8.47	76.30	9.21
MED(07) (Ref. 52)	2.3	75	4.90	1.80	6.70	83.30	11.64
MSF(07) (Ref. 52)	3	80	6.38	4.00	10.38	60.28	7.28
SWRO(07a) (Ref. 52)	5	0	10.67	0.00	10.67	60.58	7.32
SWRO(07b) (Ref. 56)	4.5	0	9.60	0.00	9.60	67.31	8.13
MED(08) (Ref. 52)	2	80.6	4.25	1.93	6.20	104.20	12.58
MSF(08) (Ref. 52)	3	80.6	6.38	4.03	10.41	60.09	7.26
SWRO(08) (Ref. 52)	5.5	0	11.73	0.00	11.73	55.07	6.65
SWRO(09) (Ref. 46)	3.88	0	8.28	0.00	8.28	78.07	9.43
SWRO(12) (Ref. 46)	3.44	0	7.34	0.00	7.34	88.05	10.63
MED(16a) (Ref. 54)	2.5	108	5.32	2.59	7.91	81.53	9.85
MED(16b) (Ref. 55)	1.82	63.97	3.87	1.54	5.41	119.26	12.36
MED(16c) (Ref. 55)	1.68	56.18	3.57	2113	3.57	131.01	15.82
MSF(16) (Ref. 55)	4	56.18	8.51	2.81	11.32	55.86	6.75
SWRO(16a) (Ref. 46)	2.96	0	6.31	0.00	6.31	102.33	12.36
SWRO(16b) (Ref. 54)	5	0	10.67	0.00	10.67	60.58	7.32
Average	4.38	85.5	10.67

primary fuel proportion utilization by cogeneration components based on exergy and energy analysis.

With the relative contributions of exergy destruction in cogeneration processes accurately determined, the amount of primary energy consumption attributed at an exergy or top-brine temperature (TBT) level to a process can now be readily computed. Using such a methodology, the universal performance ratio (UPR) for any desalination process, as presented in Eq. (2), can be determined,³⁷ i.e.,

$$UPR = \frac{h_{fg}}{3.6 \sum_{i=1}^2 \left\{ \varphi_1 \left(\frac{kWh_{elec}}{m^3} \right) + \varphi_2^{(TBT)} \left(\frac{kWh_{ther}}{m^3} \right) \right\}}, \quad (2)$$

where φ_1 and $\varphi_2^{(TBT)}$ are the conversion factors needed for converting the derived electricity and thermal input at a given top-brine temperature (TBT) to the respective primary energy. The h_{fg} is the latent heat of potable water produced, i.e., 2326 kJ/kg. Most of the literatures available is based on the conventional energetic approach for performance evaluation.^{38–45} Over 20 published articles on CCGT power and desalination are analyzed to find average conversion factors φ_1 , $\varphi_2^{(TBT)}$ as delineated in Table III. Based on the primary energy consumption, the detailed UPR values and the alternative figure of merit, m^3/kWh_{pe} , are determined for the published data of desalination plants, as shown in Table IV.

Chronologically over the last three decades, the trend of UPR values is increasing steadily from a low value of 40 to a high value of 113, as shown in Figure 3. The direct figure of merit for desalination, i.e., the m^3/kWh_{pe} is also presented on the secondary axis of Figure 3. It can be seen that the MED (11.1% TL) has slightly better efficiency than SWRO (7.45% of TL) and MSF (6.4% of TL) methods. Despite a gradual rising desalination efficiency of all desalination methods over the past 3 decades, the desalination efficiencies are merely hovering less than 15% of the TL where the TL has a UPR* of 828 or an ideal production of 1.282 m^3/kWh_{pe} . From these comparisons, all scientists and engineers of the desalination community should not rest their laurels as their existing desalination efficiency is far from the TL. Much effort to improve desalination efficiency is urgently needed so as to approach the goals of future sustainable desalination. Although nature is always harsh to mankind, our experiences in the heat

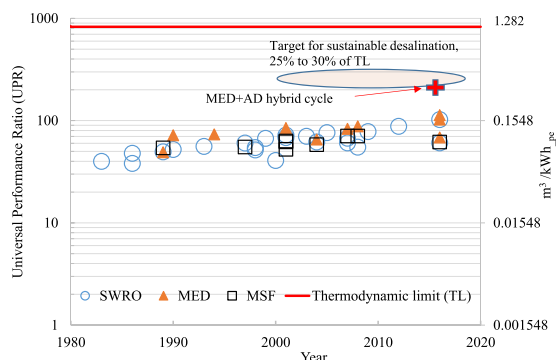


FIG. 3. A chronological trend in the primary-energy based performance ratio (PR) of all desalination plants from 1983 to 2016. Despite a gradual increase in the efficiency, all desalination methods available today are far remote from the thermodynamic limit (TL).

engine cycles have demonstrated that it is plausible to reach up to 30% of the ideal limit even for future desalination. We opine that the opportunity for improving efficiency of desalting processes is good, both in the materials development and excellence in thermodynamic synergy for the thermally driven hybrid cycles, for example, the MEDAD cycle as shown in Figure 3.

Recent publications appearing in the literature^{58–71} have made great strike towards improving the efficacy of practical desalination methods. In one example, the hybridization of the conventional MED method with the adsorption desalination (AD) cycles has been extensively investigated at the King Abdullah University of Science and Technology. The AD cycle^{72–77} is attached to the bottom-brine stage of the MED, acting as a vapor compressor to lower the bottom-brine temperature of MED. Owing to the excellent thermodynamic synergy between these cycles, the water production yield of the MED stages is almost double while the thermal heat input to the MED remains unchanged. The additional thermal heat input is the regeneration heat required for desorption of the adsorbent that facilitated the batch-operation of AD cycles. Our experiments show a quantum jump in the figure of merits for efficiency where the universal performances ratio (UPR) attained by the MED + AD cycles, or MEDAD in short, has increased from 113 to 175, as denoted by the red-colored cross symbol of Figure 3. This demonstrates that a “quantum jump” in the UPR of desalination is only possible when there is a methodology shift in the desalination technology. Otherwise, the improvement in desalination efficiency can merely be of a marginal increase, as evident in the gradual slope improvement, over a three decade period, of the mentioned methods of Figure 3.

By specifying the primary energy consumption in all desalination methods, it presents a whole fresh paradigm for efficiency comparison. The exergy destruction analysis for desalination processes is deemed more accurate and fair, as it subsumed the conversion losses as well as the exergy destruction needed by the processes in a cogeneration configuration. The revised universal performance ratio (UPR) or the alternative m^3/kWh_{pe} revealed that the existing efficiency of desalination methods is not better than 15% of the ideal limit of desalination. The challenge now is to seek a higher efficiency goal for future sustainable desalination, typically up to 30% of the thermodynamic limit or an equivalent target of 0.3 m^3/kWh_{pe} . Such an efficiency target can be achieved through either the hybridization between existing desalination processes to achieve excellent thermodynamic synergy between them, as demonstrated by the MEDAD processes, or to seek a quantum improvement in the realm of high permeable flux of membrane materials. Accumulated experiences of hybrid design of desalination processes have confirmed a plausible focus direction for achieving sustainable desalination.

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