A New Approach to Efficiency Evaluation of Desalination

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Water, Energy and Environment Nexus:

- Processes – thermal or membrane-based
- $> 9.5 \text{ kWh}_{\text{pe}} / \text{m}^3$
- CO2 emission – 240 $M$ ton/day
- Brine & chemicals discharge

Water (by Desalination)

New innovative solutions are needed to ensure future sustainability

Energy

Environment

Is the desalination process sustainable?
Types of Practical Seawater Desalination plants

138,000 m³/day, 2006, Singapore (TUAS) at US$165 m, water cost = US$0.65/m³, SEC = 4.2 kWh_{elec}/m³.

68,190 m³/day, 2012, Yanbu (5-stages & PR> 9) MED-TVC, TBT= 60°C, BBT= 45°C, SEC =2.5 kWh_{elec}/m³, Thermal= 78 kWh_{ther}/m³.

One million m³/day hybrid MSF at Ras Al-Khair (2017), collocated with a 2400 MW power plant (SWCC) at investment cost of US$6.1b.

Average Specific Energy Consumption (1983-2016)

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<thead>
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<th>Reverse Osmosis (22 plants)</th>
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<tr>
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<td>2.6</td>
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<tr>
<td>Thermal Input (kWh_{ther}/m³)</td>
<td>-</td>
<td>Thermal Input (kWh_{ther}/m³ at 60°C)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Thermal Input (kWh_{ther}/m³ at 120°C)</td>
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Questions: (1) Which of the three processes is more efficient ?
(2) Are the derived units, kWh, a suitable units to be used for the efficiency comparison ?
Adequacy of Energy Units?

- Are the derived energies are equal thermodynamically?
- If not, what datum is needed for comparison of processes?

Thermodynamically, the datum units is work, e.g., *primary energy*.

- For a process stream, the available work or exergy is analyzed.
- Across a device, the exergy destruction to execute or consumed in the process to achieve a useful output, i.e., Gibbs equation;

\[ \Delta G = \dot{m} \{ \Delta h - T_0 \Delta s \} \]
Existing Efficiency Definition:

- The current PRs of desalination processes are defined by *derived energy*, i.e.,

\[
PR = \left( \frac{\text{Equivalent heat of evaporation of distillate production}}{\text{Energy input}} \right) = \frac{2326 \frac{kJ}{kg}}{3.6 \times \left\{ \frac{kWh_{\text{elec}}}{m^3} \right\} + \left\{ \frac{kWh_{\text{ther}}}{m^3} \right\}}
\]

Inherent Weaknesses:

(i) Ignore the conversion efficiency of power & boiler plants,

(ii) No distinction between the *quality or grade of energy* at input,

(iii) Predicated on an arbitrary constant, 2326.
Conventional Conversion Method

Only single useful output

An example of converting primary energy to derived energy (Cooling)

Power plant

\[ \eta = 0.35 \]

Exergy destruction = 60±4%

1 kWh\(_e\)

Exhaust

Chillers

\[ \text{COP}_{\text{chiller}} = 6 \]

Exergy destruction = 75±4%

Condenser

Cooling at 6 kWh\(_t\)

Low grade Derived Energy (Cooling)

Exergy approach:
Combined Exergy destruction = 0.62 \times 0.75 = 0.47

Enthalpy approach: \(\text{COP}_{\text{pe}} = \frac{6}{2.86} = 2.1\)

Unit cooling requires \(\frac{1}{\text{COP}_{\text{pe}}} = \frac{1}{2.1} = 0.47\) units of primary energy. (Same results from exergy method as this is a single useful output system)
Advanced Cogeneration method

Two or more useful output in cascaded manner

GT cycle consumes 75±3% of the input (fuel) exergy

Remaining 23±2% is recovered by HRSG

2±0.5% of exergy exit as exhaust gases

Enthalpic analysis is inadequate for apportionment of primary energy. An exergy approach is needed.

Steem turbines utilize 20±3% of the fuel exergy

Thermal Desalination consumes 3±1% of fuel exergy
Conversion factors?
(by exergy destruction analysis)

Electricity is a high grade energy, it needs $2.12 \text{kWh}_{\text{pe}}$ to produce $1 \text{kWh}_{\text{elec}}$.

Thermal heat is a low grade energy, it merely needs $29.5 \text{kWh}_{\text{th}}$ at 60°C to be equivalent to $1 \text{kWh}_{\text{pe}}$.

Primary energy

Derived energy

2.12 \text{kWh}_{\text{pe}}

1 \text{kWh}_{\text{elec}}

Primary energy

Derived energy (60 C)

1 \text{kWh}_{\text{pe}}

29.5 \text{kWh}_{\text{thermal of low grade energy}}

$$\varphi_{\text{elec}} = \frac{1}{0.47}$$

$$\text{UPR} = \frac{2326 \{\text{kJ/kg}\}}{3.6 \times \varphi_{\text{elec}} \text{Wh}_{\text{elec}}/m^3 + \varphi_{\text{ther}} \text{Wh}_{\text{ther}}/m^3}$$

$$\varphi_{\text{thermal@60C}} = \frac{1}{29.5}$$
Desalination PR Comparison: Thermal & RO 60+ Globally Installed Plants

<table>
<thead>
<tr>
<th>Ref</th>
<th>Method</th>
<th>Elec</th>
<th>thermal</th>
<th>PE</th>
<th>PR</th>
<th>%TL</th>
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<td>Ref.1</td>
<td>SWRO(16a)</td>
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- Minimum separation work = $0.78 \text{kWh}_e/\text{m}^3$
- $E(kJ/kg) = \frac{0.78 \text{ KWh}_h}{m^3} \times \frac{3600 \text{sec}}{h} \times \frac{m^3}{1000 \text{kg}} = 2.8 \text{ KJ/kg}$
- Thermodynamic Limit (TL) = $\frac{2326 \text{ KJ/kg}}{2.8 \text{ KJ/kg}} = 828$

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**Electricity usage:** kWh\(_{elec}\)/m\(^3\)
**Thermal energy:** kWh\(_{ther}\)/m\(^3\)
**Primary energy:** kWh\(_{pe}\)/m\(^3\)
**Performance ratio (PR):**

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**UPR of Seawater Desalination Method and the m³/kWhₚₑ**

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- **Primary Energy (kWhₚₑ/m³)**
  - **0.09 m³/kWhₚₑ**
  - **0.135 m³/kWhₚₑ**
  - **0.082 m³/kWhₚₑ**
Example 1: MED+AD Desalination Pilot Plant at KAUST

- Video: https://www.youtube.com/watch?v=-ZnuOGrTohk
- On the road to water sustainability in the Gulf, Shahzad M.W. and Kim Choon Ng, Nature Middle East, April 28th, 2016, doi:10.1038/nmiddleeast.2016.50

Solar Powered AD Pilot Plant (2013)

Integration of MED and the AD pilot plant
With present MEDAD plant, the new PR= 110 (1.25)
=137.5

(PR)_{MED} = \frac{2326}{3.6 \left( \frac{1.8 + 214}{0.47 + 29.5} \right)} = 58.3

(PR)_{MED+AD} = \frac{2326}{3.6 \left( \frac{2.2 + 122}{0.47 + 29.5} \right)} = 73.3

25% increase
UPR of Hybrid MEDAD with 12 stages:
- Achieving Sustainable Desalination
Understanding the Efficacy of Seawater Desalination

A history of primary energy consumption as the datum for comparison

Thermodynamic limit for seawater desalination

The next innovation step: achieving the Sustainable Desalination of 0.3 m³/kWh_pe

Universal Performance Ratio (UPR)


YEAR

1.282

5th Generation Technology

0.1548

m³/kWh_pe

0.01548

Technology improvement with Cogeneration (CCGT+MSF/MED)

0.001548

Improvement in boiler technology: burning less fuels

A combination of Boiler & MSF

3rd Generation

MED

4th Generation

SWRO

Thermodynamic limit (TL)

1st Generation

Primitive Desaltor

2nd Generation

MSF

3rd Generation

A combination of Boiler & MSF

4th Generation

SWRO
Closing: - Optimal utilization of thermodynamic synergy for the cogeneration of power and water

On the road to water sustainability in the Gulf, Shahzad M.W. and Kim Choon Ng, *Nature Middle East*, April 28th, 2016, doi:10.1038/nmiddleeast.2016.50,
A New Approach to Sustainable Desalination

- Adsorption research is scaled-up for a commercial pilot at the Solar Village, KACST.

A MOU signing on 21st February, 2017, between four parties, KACST_MEDAD/KAUST_SWCC_AWT for planning a scaled-up MEDAD hybrid plant (2,000m³/day) in one of the SWCC sites.

Front row: Eng. Ali Bin AbdurRahman AlHazmy (Governor of SWCC), H.E. Prince Turki Bin Saud (Executive President of KACST), Joseph Ng (CEO of MEDAD), and Mr. Khalid AlHabib (Director of Engineering, Advanced Water Technology). Back row: Mr. Nadhmi AlNasr (EVP, KAUST), H.E., Khalid A. AlFalih, Minister of Energy, Industry and Mineral Resources, third person Dy President of KACST).

The commercial pilot at Solar Village of 75 m³/day and 2 MW cooling, built jointly by KACST_MEDAD KAUST, treating the RO rejects.