تحت رعاية معالي رئيس مجلس الوزراء المصري المهندس شريف إسماعيل
مؤتمر تحلية المياه الحادي عشر في البلدان العربية
UNDER THE PATRONAGE OF THE EGYPTIAN PRIME MINISTER ENGINEER SHERIF ISMAIL
11TH WATER DISALINATION CONFERENCE IN THE ARAB COUNTRIES
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A New Approach to Efficiency Evaluation of Desalination

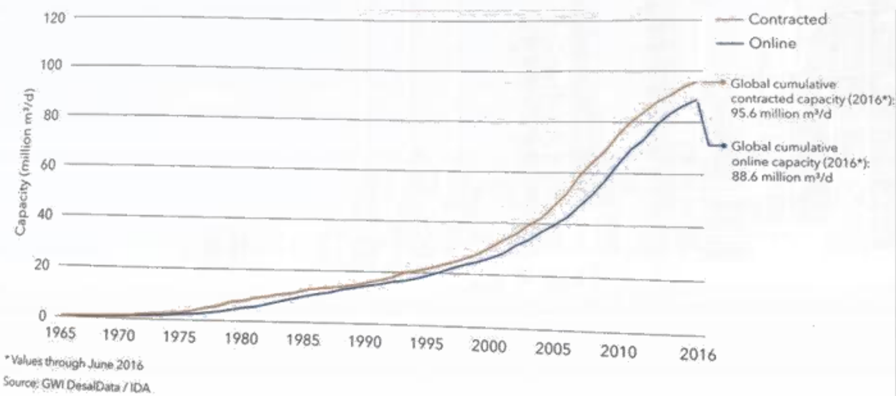
Kim Choon Ng[1] and Muhammad W Shahzad[2]

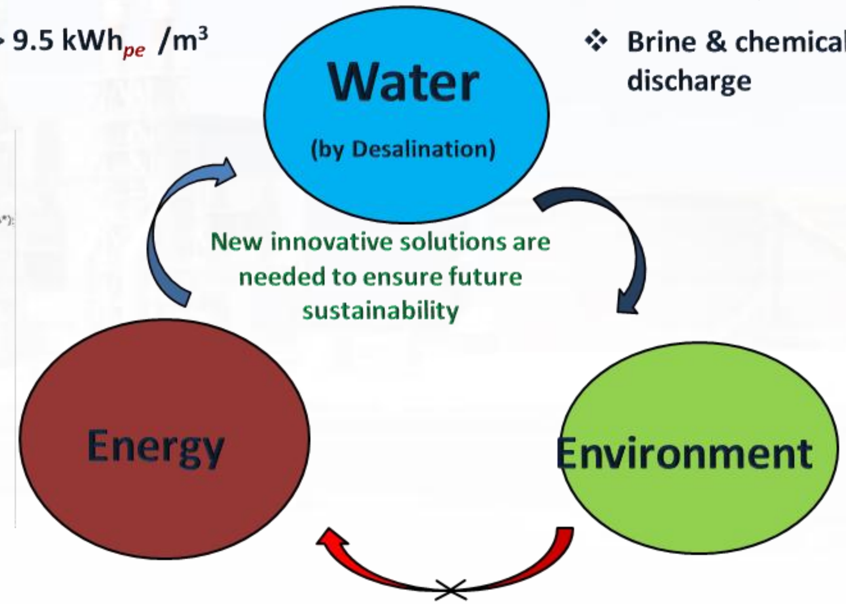
[1]Professor, [2]Research Scientist,
WDRC, King Abdullah University of Science & Technology (KAUST)
Thuwal, SA.
Email: Kimchoon.ng@kaust.edu.sa

Water, Energy and Environment Nexus:

- Processes –thermal or membrane-based
- > 9.5 kWh_{pe} /m^3

- CO_2 emission – 240 *M* ton/day
- Brine & chemicals discharge





Is the desalination process sustainable ?

Types of Practical Seawater Desalination plants

138,000 m^3/day, 2006, Singapore (TUAS) at US$165 m, water cost = US$0.65/m^3, SEC = 4.2 $kWh_{\_elec}$/ m^3.

(http://attfile.konetic.or.kr/konetic/xml/descon/11A1A0700114.pdf)

68,190 m3/day, 2012, Yanbu (5-stages & PR> 9) MED-TVC, TBT= 60°C, BBT= 45°C, SEC =2.5 kWh_{-elec}/m^3, Thermal= 78 $kWh_{\_ther}$/m^3.

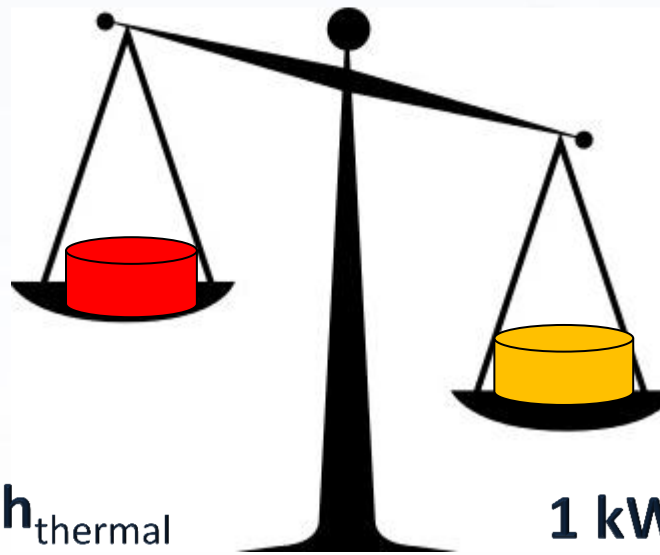
One million m^3/day hybrid MSF at Ras Al-Khair (2017), collocated with a 2400 MW power plant (SWCC) at investment cost of US$6.1b.

Average Specific Energy Consumption (1983-2016)

Reverse Osmosis (22 plants)		**Multi-Effect Distillation** (10 plants)		**Multi-Stage Desalination** (9 plants)	
Electricity ($kWh_{\_elec}$/m^3)	**5.2**	Electricity ($kWh_{\_elec}$/m^3)	**2.6**	Electricity ($kWh_{\_elec}$/m^3)	**3.75**
Thermal Input ($kWh_{\_ther}$/m^3)	-	Thermal Input ($kWh_{\_ther}$/m^3 at 60°C)	**76.0**	Thermal Input($kWh_{\_ther}$/m^3 at 120°C)	**79.5**
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 kWh_{elec} & $kWh_{thermal}$ the same thermodynamically?



1 $kWh_{thermal}$ **1 kWh_{elec}**

Derived Energies – use for convenience

- 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.,

$$PR = \left(\frac{\text{Equivalent } heat\ of\ evaporation\ of\ distillate\ production}{Energy\ input}\right) = \frac{2326\left\{\frac{kJ}{kg}\right\}}{3.6\ x \underbrace{\left\{\frac{kWh_{elec}}{m^3}\right\} + \left\{\frac{kWh_{ther}}{m^3}\right\}}_{Derived\ Energy\ ?}}$$

➢ Inherent Weaknesses:

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

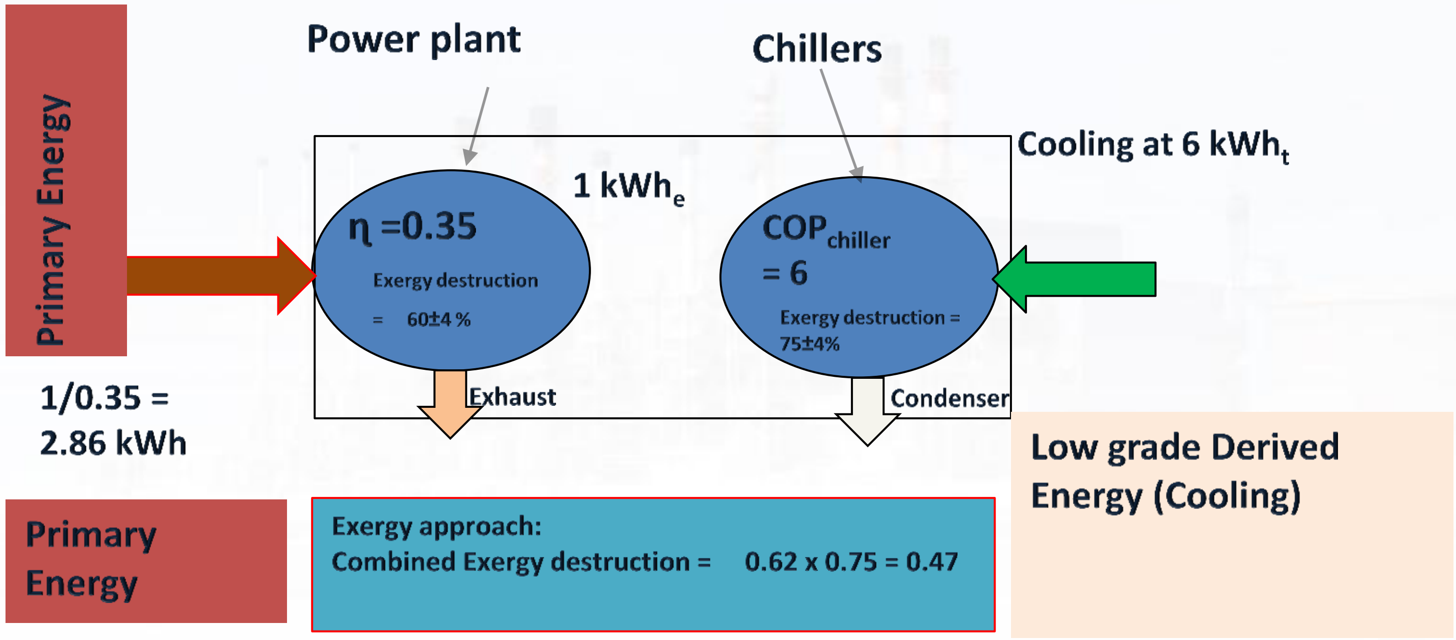
(ii) No distinction between the quality or grade of energy at input,

(iii) Predicated on an arbitrary constant, 2326.

Conventional Conversion Method

<u>**Only single useful output**</u>

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



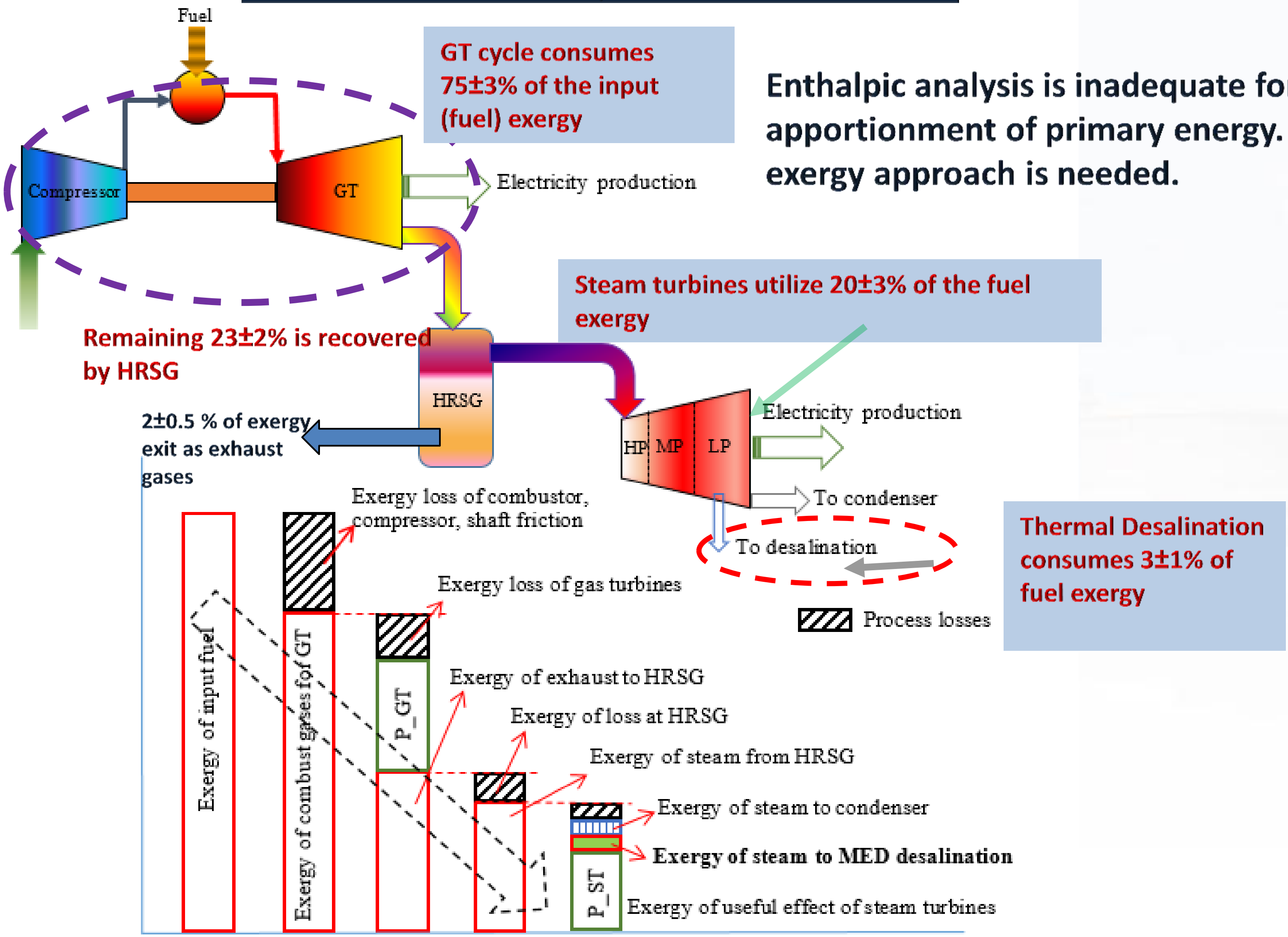
Enthalpy approach: COP_{pe} = 6/2.86 = 2.1

Unit cooling requires 1/COP_{pe} =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

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

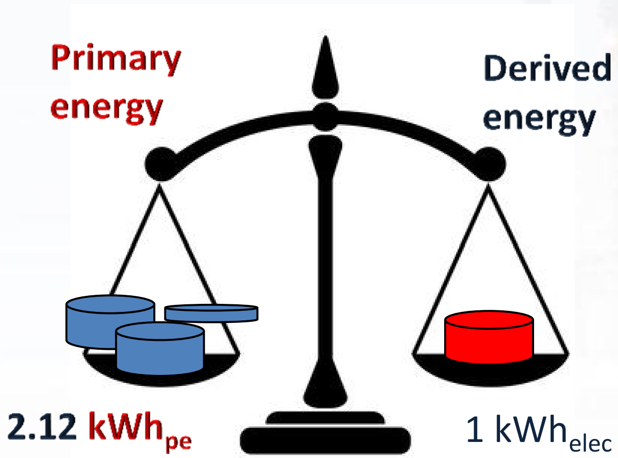


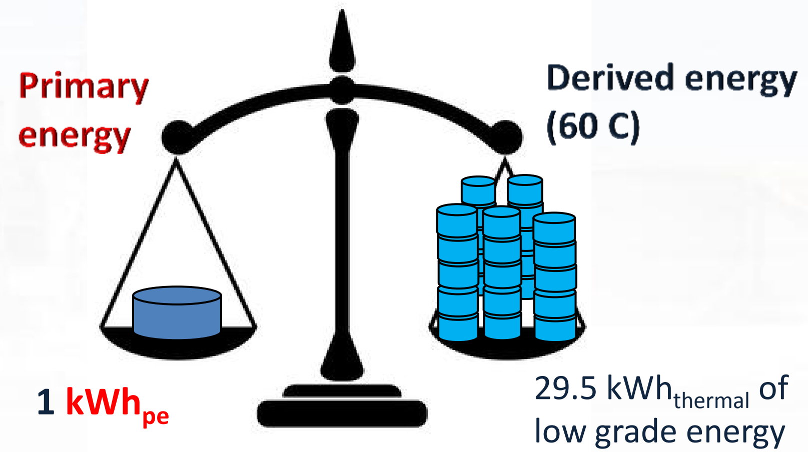
Conversion factors?

(by exergy destruction analysis)

Electricity is a high grade energy, it needs **2.12 kWh_{pe}** to produce 1 kWh_{elec}

Thermal heat is a low grade energy, it merely needs 29.5 kWh_{th} at 60°C to be equivalent to **1 kWh_{pe}**





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

$$\text{UPR} = \frac{2326 \left\{\frac{kJ}{kg}\right\}}{3.6\ x \underbrace{\left\{\varphi_{\text{elec}} \frac{kWh_{elec}}{m^3}\right\} + \left\{\varphi_{ther} \frac{kWh_{ther}}{m^3}\right\}}_{Primary\ Energy}}$$

$$\varphi_{thermal@60C} = \frac{1}{29.5}$$

Desalination PR Comparison: Thermal & RO
60+ Globally Installed Plants

	Elec	therma	PE	PR	%TL
(sample)	3.00	0.00	5.65	114.32	13.81
SWRO(83)	7.58	0.00	14.28	45.25	5.46
SWRO(86a)	6.32	0.00	11.91	54.27	6.55
SWRO(86b)	7.93	0.00	14.94	43.25	5.22
MED(89)	5.00	65.93	11.66	55.42	6.69
MSF(89)	4.30	80.76	10.84	59.58	7.20
SWRO(89)	6.11	0.00	11.51	56.13	6.78
MED(90)	2.35	104.00	7.96	81.17	9.80
SWRO(90)	5.80	0.00	10.93	59.13	7.14
SWRO(93)	5.40	0.00	10.17	63.51	7.67
MED(94)	2.90	68.74	7.80	82.85	10.01
MSF(97)	4.20	80.76	10.66	60.63	7.32
SWRO(97)	5.02	0.00	9.46	68.32	8.25
SWRO(98a)	5.85	0.00	11.02	58.63	7.08
SWRO(98b)	5.56	0.00	10.47	61.68	7.45
SWRO(99)	4.51	0.00	8.50	76.04	9.18
SWRO(00)	7.42	0.00	13.98	46.22	5.58
MED(01)	2.30	71.67	6.77	95.47	11.53
MSF(01a)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
MSF(01b)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
MSF(01c)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
SWRO(01a)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
SWRO(01b)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
SWRO(03)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
MED(04)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
MSF(04)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
SWRO(04)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
SWRO(05)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
MED(07)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
MSF(07)	3.00	80.00	8.37	77.20	9.32
SWRO(07a)	5.00	0.00	9.42	68.59	8.28
SWRO(07b)	4.50	0.00	8.48	76.21	9.20
MED(08)	2.00	80.60	6.51	99.31	11.99
MSF(08)	3.00	80.60	8.39	77.01	9.30
SWRO(08)	5.50	0.00	10.36	62.36	7.53
SWRO(09)	3.88	0.00	7.31	88.39	10.68
SWRO(12)	3.44	0.00	6.48	99.70	12.04
MED(16a)	2.50	108.00	8.38	77.11	9.31
MED(16b)	1.82	63.97	5.60	115.34	13.93
MED(16c)	1.68	56.18	5.07	127.35	15.38
MSF(16)	4.00	56.18	9.44	68.41	8.26
SWRO(16a)	2.96	0.00	5.58	115.87	13.99
SWRO(16b)	5.00	0.00	9.42	68.59	8.28
	1.80	0.00	3.39	190.53	23.01
SWRO(16c)	3.96	0.00	7.46	86.61	10.46
SWRO(16d)	3.50	0.00	6.59	97.99	11.83

Minimum separation work= $0.78 kwh_e/m^3$

$$E\left(\frac{kJ}{kg}\right) = \frac{0.78\ KWh}{m^3} \times \frac{3600 sec}{h} \times \frac{m^3}{1000 kg} = 2.8\ KJ/kg$$

$$\text{Thermodynamic Limit (TL)} = \frac{2326\ kJ/kg}{2.8\ kJ/kg} = 828$$

Ref		Method	Elec	thermal	PE	PR	%TL
Ref.1	2016	SWRO(16a)	2.96	0.00	5.17	124.98	15.09
Ref.10	2016	MED(16b)	1.82	63.97	5.35	120.72	14.58
Ref.8	2007	MSF(07)	3.00	80.00	7.96	80.99	9.78

Electricity kWh_{elec} /m3

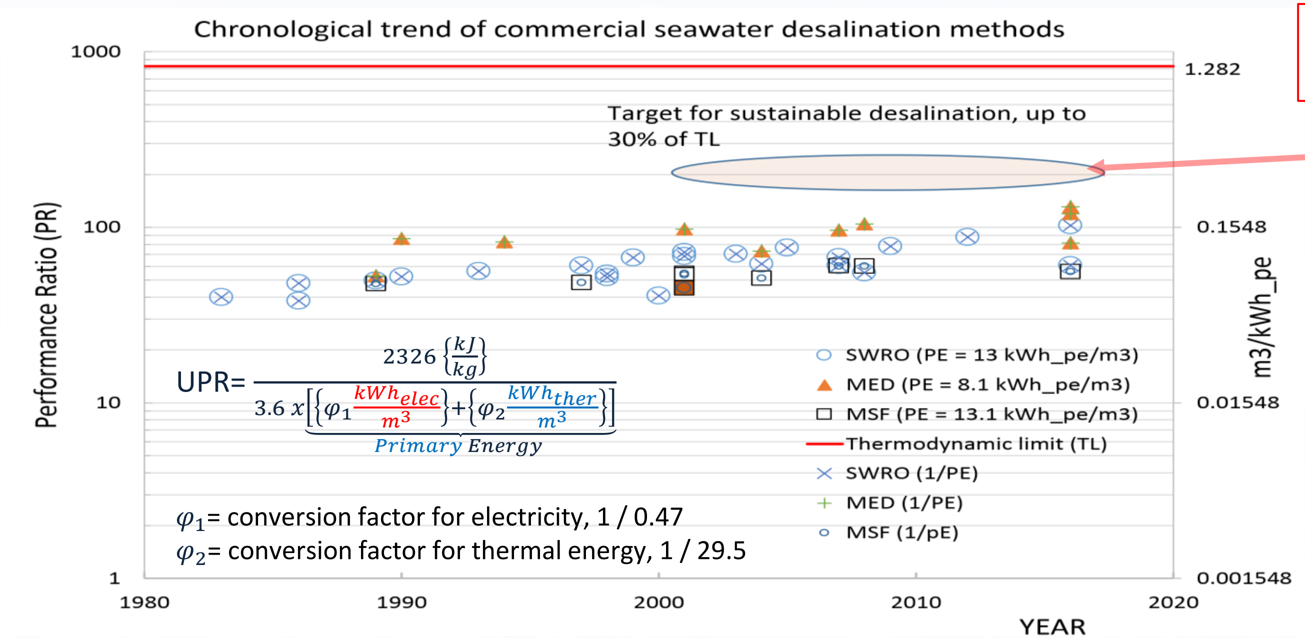
Thermal kWh_{ther} /m3

Primary Energy kWh_{pe} /m3

Performance ratio (PR)

[1] Sanz, M. A. (Deg ... on development (2012) WEX 2012
[2] Al-Shammiri, M. ... Desalination, 126, 45-59
[3] Tonner, J., Barriers to thermal desalination in the United States (2008) Desalination and water purification research and development program report, US Department of the Interior
[4] Economic and Social Commission for West Asia, Water desalination technologies in the ESCWA member countries (2001) ESCWA, UN
[5] Wade, N. M., Distillation plant development and cost update (2001) Desalination, 136, 3-12
[6] Borsani, R., Rebagliati, S., Fundamentals and costing of MSF desalination plants and comparison with other technologies (2005) Desalination, 182, 29-37
[7] Blank, J. E., Tusel, G. F., Nisan, S., The real cost of desalted water and how to reduce it further (2007) Desalination, 205, 298-311
[8] IRENA, Water desalination using renewable energy (2012) IEA-ETSAP and IRENA Technology Brief 112, IRENA
[9] Ng. K. C., Energy, Water and Environment Nexus for Future Sustainable Desalination (2016) SET 2016, International Conference on Sustainable Energy Technology
[10] Ihm, S., Najdi, O. Y., Hamed, O. A., Jun, G., Chung, H., Energy cost comparison between MSF, MED and SWRO: Case studies for dual purpose plants (2016) Desalination, 397, 116-125
[11] Lemes, R., Talavera, J., Falcon, R., Arocha, R., Curbelo, J., Platas, V., Lorenzo, L., Zarzo, D., Evolution of production and energy saving in SWRO plant of LAS Palmas III (2011) IDA World Congress
[12] Farooque, A., Jamaluddin, A., Al-Reweli, A., Jalaluddin, P., Al-Marwani, S., Mobayed, A., Qasim, A., Parametric analyses of energy consumption and losses in SWCC SWRO plants utilizing energy recovery devices (2008) Desalination, 219, 137-159

UPR of Seawater Desalination Method and the m^3/kWh_{pe}



$$UPR = \frac{2326\left\{\frac{kJ}{kg}\right\}}{3.6\ x\underbrace{\left[\left\{\varphi_1 \frac{kWh_{elec}}{m^3}\right\}+\left\{\varphi_2 \frac{kWh_{ther}}{m^3}\right\}\right]}_{Primary\ Energy}}$$

φ_1= conversion factor for electricity, 1 / 0.47

φ_2= conversion factor for thermal energy, 1 / 29.5

Alternative figure of merit, $m^3/kWh_{\_pe}$

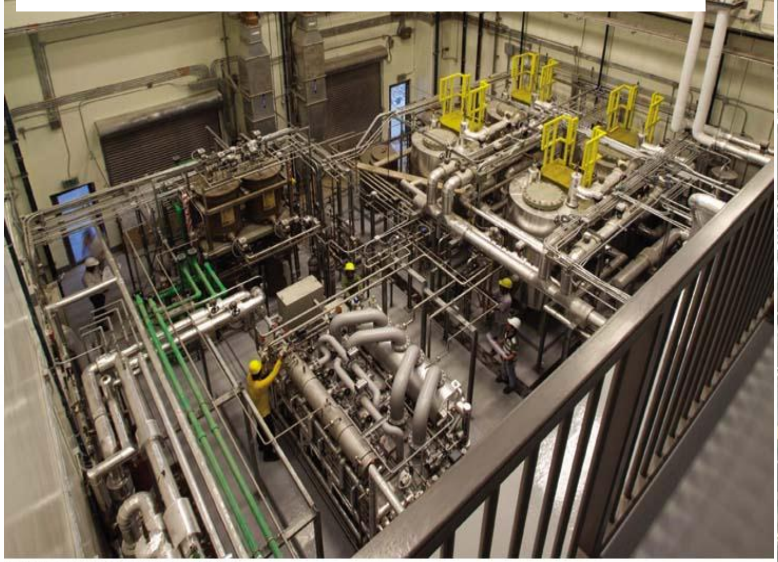
0.3 to 0.35

Reverse Osmosis (22 plants)		**Multi-Effect Distillation (10 plants)**		**Multi-Stage Desalination (9 plants)**	
Electricity ($kWh_{\_elec}/m^3$)	**5.2**	Electricity ($kWh_{\_elec}/m^3$)	**2.6**	Electricity ($kWh_{\_elec}/m^3$)	**3.75**
Thermal Input ($kWh_{\_ther}/m^3$)	-	Thermal Input ($kWh_{\_ther}/m^3$ at 60°C) $\varphi_2 = 1/29.5$	**76.0**	Thermal Input($kWh_{\_ther}/m^3$ at 180°C) $\varphi_2 = 1/18.5$	**79.5**
Primary Energy ($kWh_{\_pe}/m^3$) 0.09 m3/kWh_{pe}	**11.1**	Primary Energy ($kWh_{\_pe}/m^3$) 0.135 m3/kWh_{pe}	**7.4**	Primary Energy ($kWh_{\_pe}/m^3$) 0.082 m3/kWh_{pe}	**12.3**

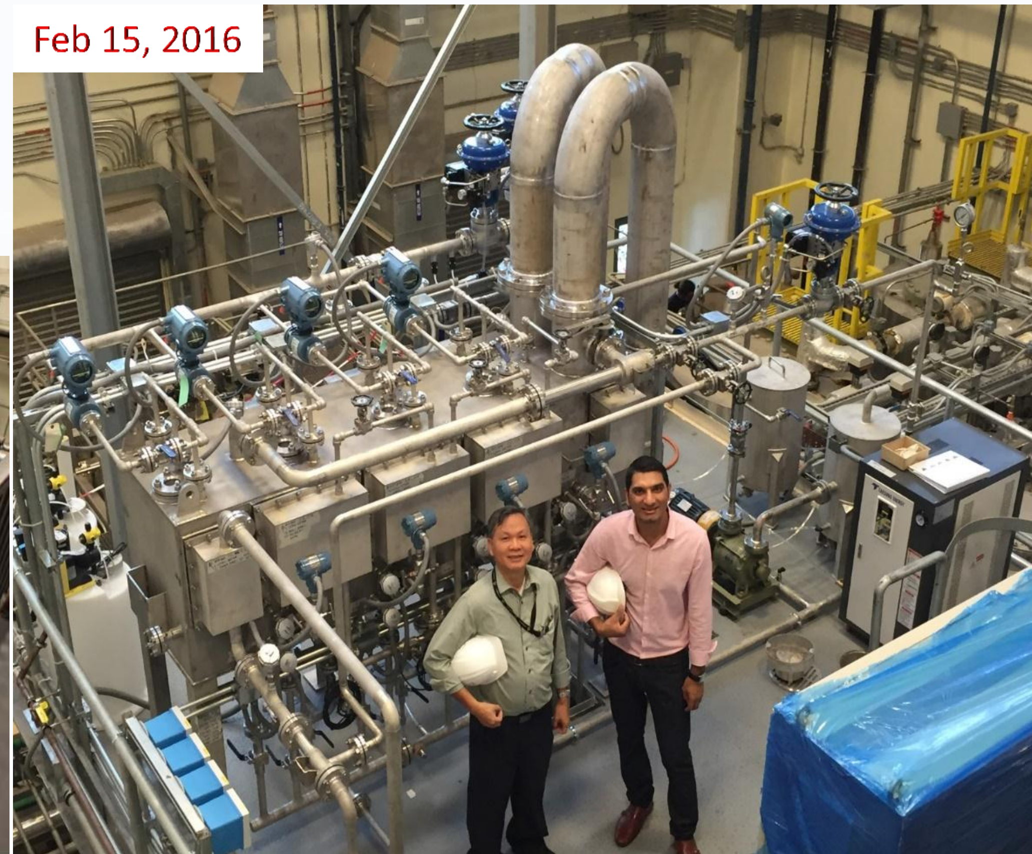
Example 1: MED+AD Desalination Pilot Plant at KAUST

- BEACON: **https://discovery.kaust.edu.sa/en/article/201/partnering-for-sustainable-fresh-water-production**
- Video: https://www.youtube.com/watch?v=-ZenuOGTohk
- Yahoo: https://uk.finance.yahoo.com/news/desalination-technology-saudi-arabia-opens-120200018.html
- *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)

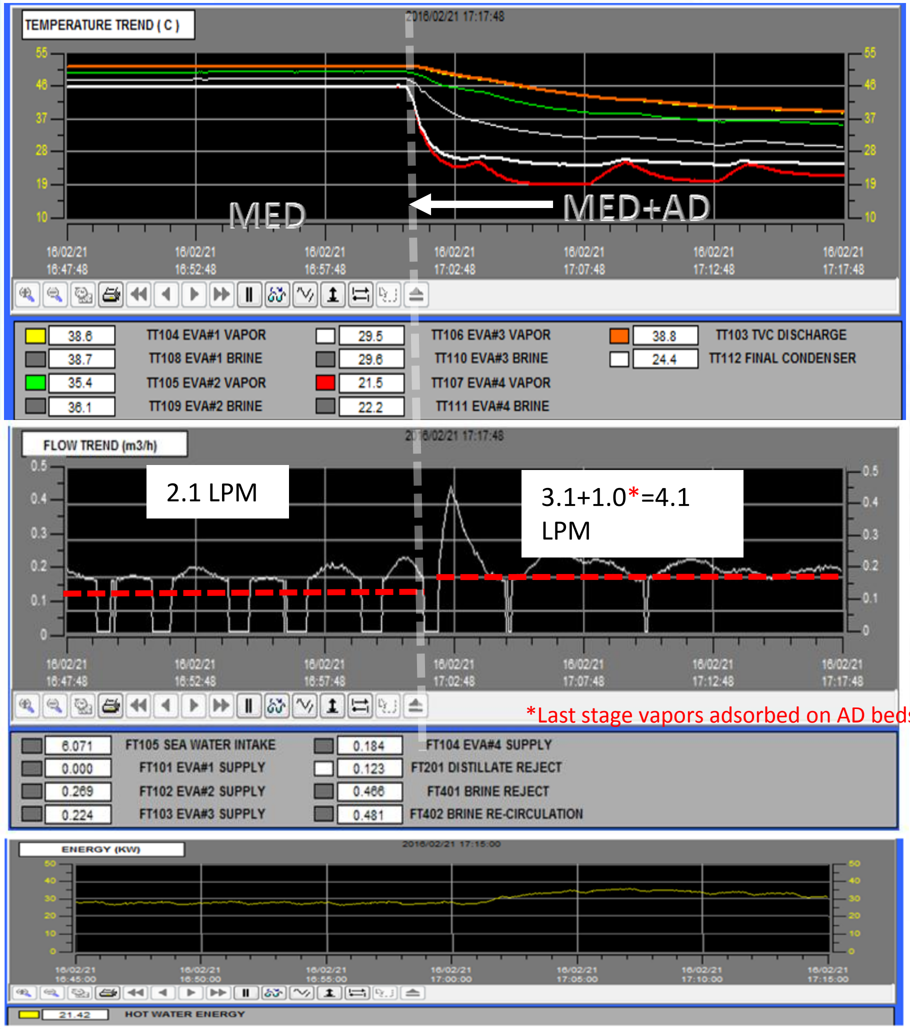


The Prototype Desalination Plant at KAUST.

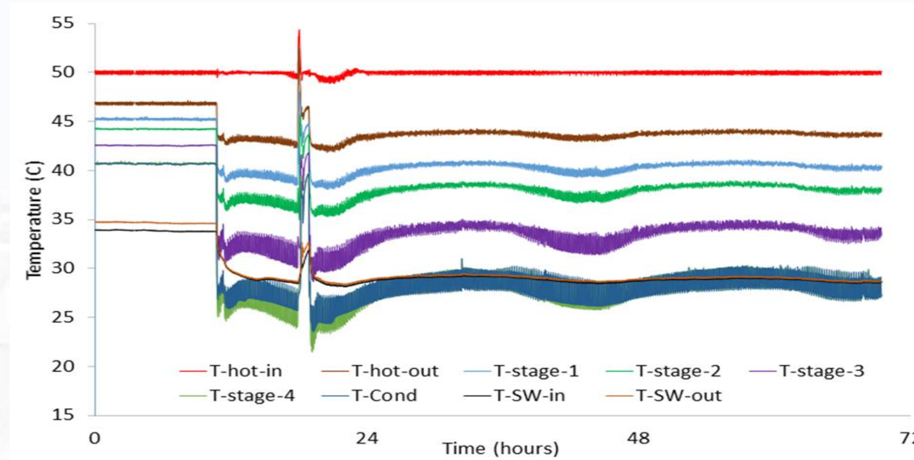


Integration of MED and the AD pilot plant

MED and MEDAD Pilot Test



Continuous operation of MEDAD at pilot plant



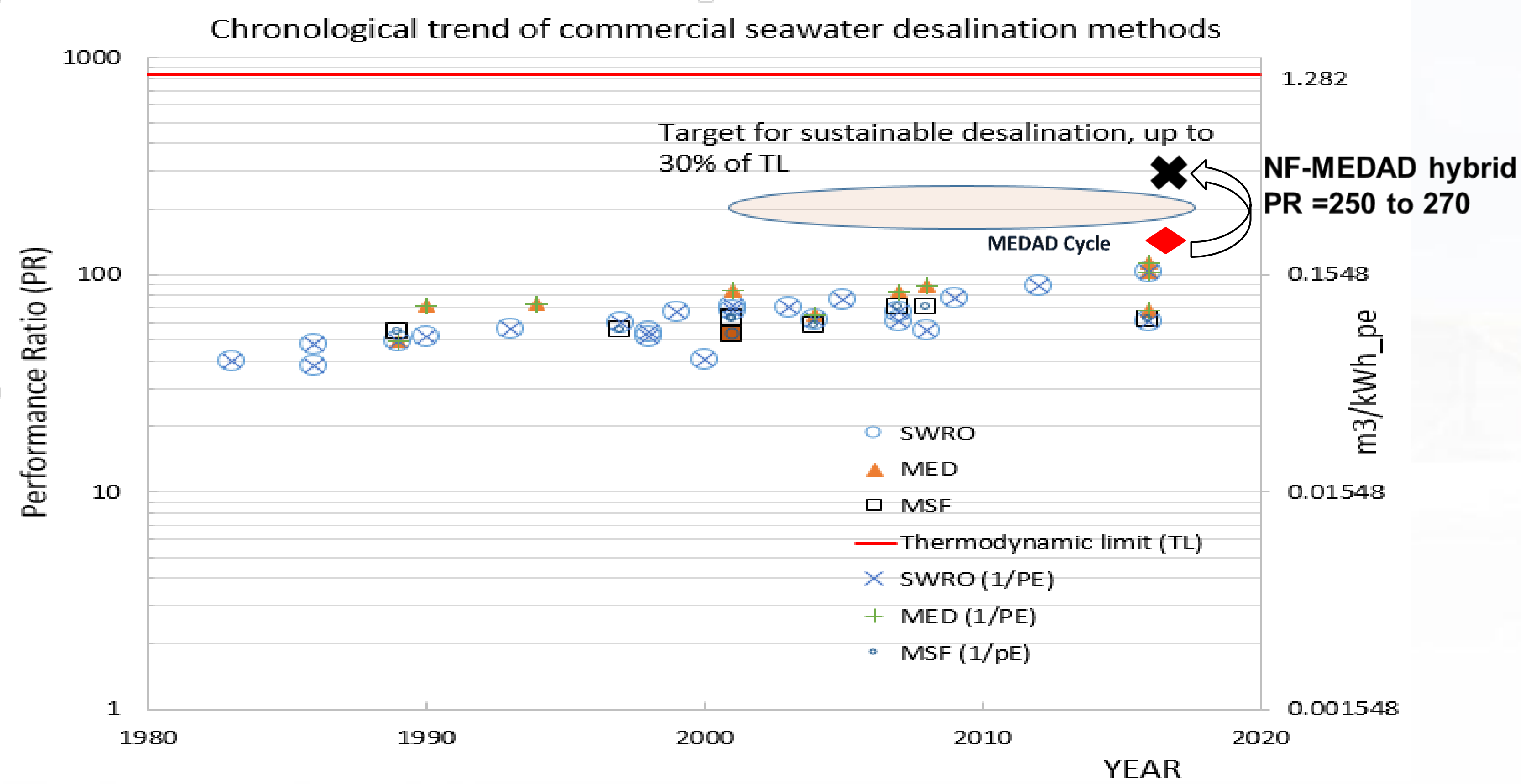
$$(PR)_{MED} = \frac{2326}{3.6\left[\frac{1.8}{0.47}+\frac{214}{29.5}\right]_r} = 58.3$$

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

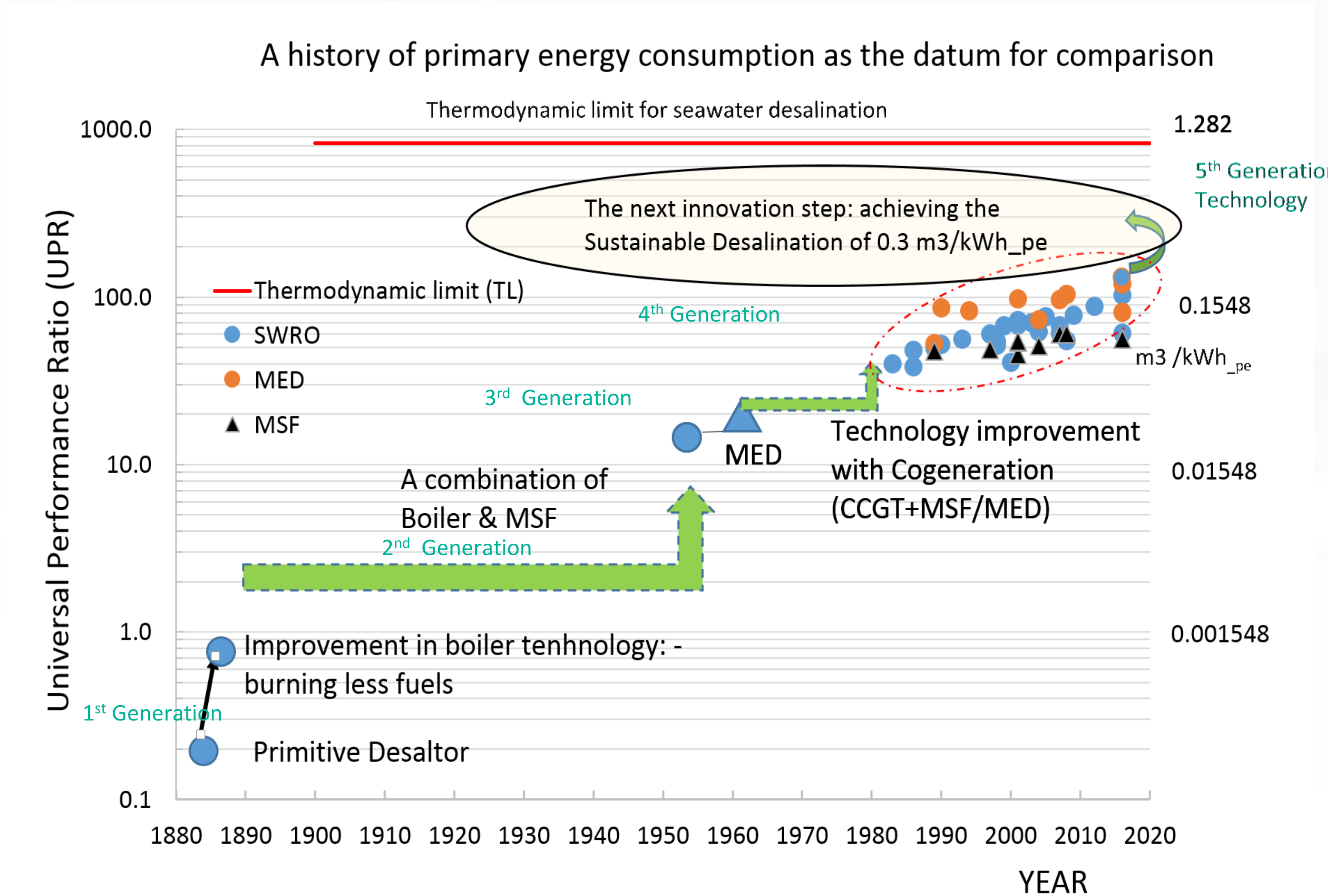
25% increase

With present MEDAD plant, the new PR= 110 (1.25) =137.5

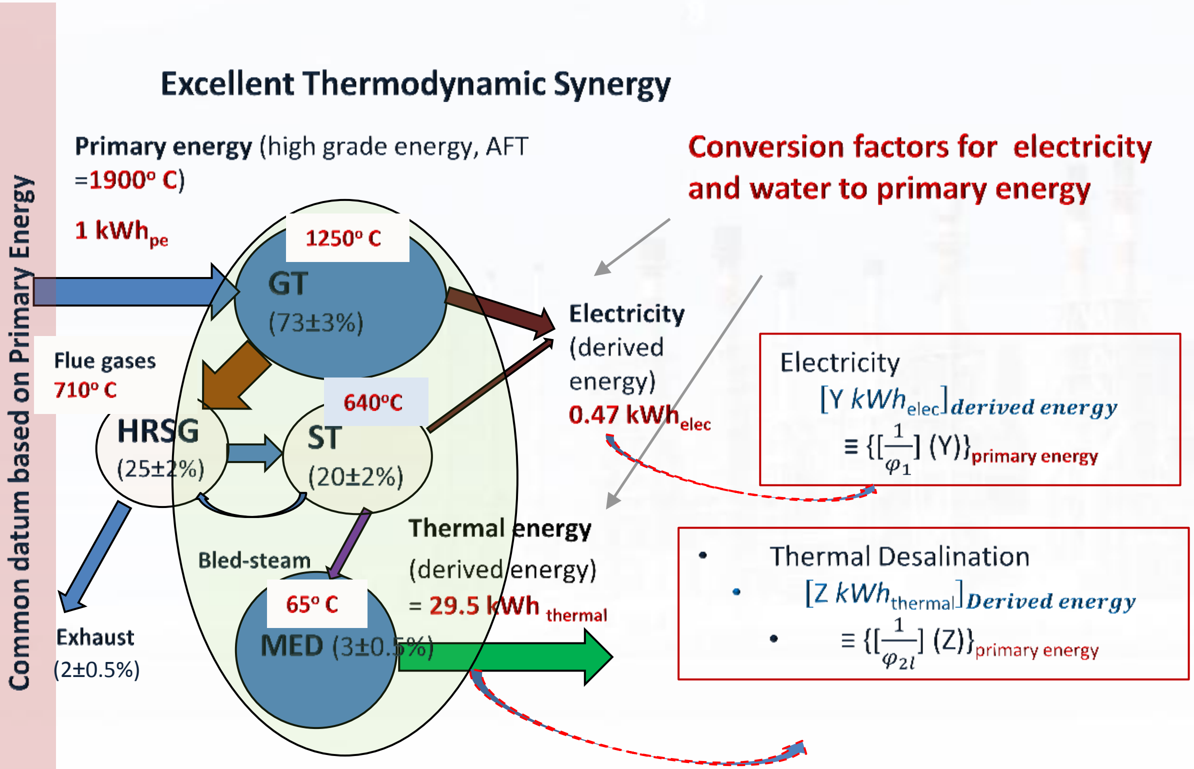
UPR of Hybrid MEDAD with 12 stages:
- Achieving Sustainable Desalination



Understanding the Efficacy of Seawater Desalination



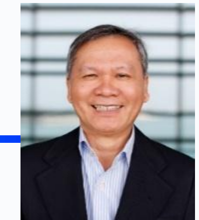
Closing: - Optimal utilization of thermodynamic synergy for the cogeneration of power and water



- Inadequacy of derived energy
- Exergy analysis is the rational basis for evaluating efficiency and cost of the systems' outputs.
- The co-location of large scale thermally-driven desalination methods (MSF/MED) in power plants reinforced the designers' wisdom, particularly in the Kingdom,
- **Hybridization favors thermally-driven systems to attain Sustainable Desalination.**

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 AbdulRahman 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 Technolgy), 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.