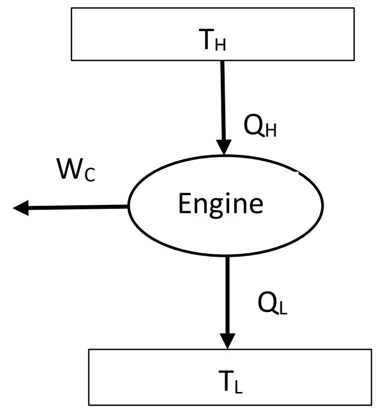
Supplementary Material 1: Carnot Heat Engines

Invoking the corollary of **Second Law** of Thermodynamics for the heat engine,

$$\frac{Q}{T} = Constant = \frac{Q_H}{T_H} = \frac{Q_L}{T_L}, \qquad \text{(A1)}$$



and from the 1st Law of Thermodynamics,

$$Q_L = Q_H - W_C \qquad \text{(A2)}$$

Substituting into the right side of equation 1, yields

$$\frac{Q_H}{T_H} = \frac{Q_H - W_C}{T_L},$$

and rearranging, we have

$$\frac{W_C}{T_L} = \left(\frac{Q_H}{T_L} - \frac{Q_H}{T_H}\right) = \frac{Q_H(T_H - T_L)}{T_L T_H},$$

Thus, the relation between Carnot work (W_C), heat transfer (Q_H) and the reservoirs temperatures (T_H, T_L) are given by

$$\frac{W_C}{(T_H - T_L)} = \frac{Q_H}{T_H}. \qquad \text{(A3)}$$

By adopting a common temperature platform between the adiabatic flame and ambient temperatures, where $T_H \rightarrow T_{adia,}$ and the ambient temperature, $T_L \rightarrow T_{o,}$ the above corollary can also be applied either to an individual or to a series of engines operating in a temperature-cascaded manner, say with heat engines $E_{1,}$ E_2 and $E_{3,}$ etc., . These engines or reverse engines emulate the equivalent Carnot work (W_C), that were derived from the actual processes operating at their respective designed temperature reservoirs. With such a platform, Equation A3 provides the standard primary energy, Q_{SPE}, which is the common energy consumption platform for diverse desalination processes available today, i.e.,

Engine 1: $$(W_{C1}) = Q_{SPE1} \frac{(T_{adia} - T_o)}{T_{adia}},$$

Engine 2: $$(W_{C2}) = Q_{SPE2} \frac{(T_{adia} - T_o)}{T_{adia}},$$

Engine 3: $$(W_{C3}) = Q_{SPE3} \frac{(T_{adia} - T_o)}{T_{adia}}.$$

Summing the Carnot work of the cascaded engines of a CCGT plant, we have

$$(W_{C1} + W_{C2} + W_{C3}) = (Q_{SPE1} + Q_{SPE2} + Q_{SPE3}) \frac{(T_{adia} - T_o)}{T_{adia}}$$

From these procedures, a common temperature platform can be equated to either a single engine or a host of cascaded engines representing the desalination processes (work or heat driven) in a desalination plant, i.e.,

, $$\frac{\sum_{i=1}^{i=n}(W_{C,i})}{\sum_{i=1}^{i=n}(Q_{SPE,i})} = \frac{(T_{adia}-T_O)}{T_{adia}} = \left(\frac{W_C}{Q_{SPE}}\right)_i \qquad \text{(A4).}$$

where *i* refers to the number of cascaded engines.

For convenience, one can also rearranged Eq. A4 in terms of the ratios of an individual to all heat or work transfers or the work transfers, i.e.,

$$\frac{Q_{SPE,i}}{\sum_{i=1}^{i=n}(Q_{SPE,i})} = \frac{W_{C,i}}{\sum_{i=1}^{i=n}(W_{C,i})} \qquad \text{(A5)}$$

where *n* refers to the number of engines. It implies that for a given process (*i*), the Carnot work ratio, between the process to the maximum available Carnot work, is directly proportional to its corresponding Q_{SPE} ratio.

In seawater desalination, the conventional way of specifying energy efficacy of a work-driven process is usually expressed in the derived energy, i.e., kWh_{elec} to a unit volume of distillate (m^3). Eq. A4 could estimate the amount of standard primary energy Q_{SPE} from the consumption of actual electricity (W_a). To relate the Carnot work (W_C) to the actual work, a Second Law efficiency as defined as

$$\eta^{"} = \frac{W_a}{W_C}, \qquad \text{(A6)}$$

where W_a and W_C are the actual and Carnot work output of an engine. These equations can be further simplified to formulate a conversion factor for a derived energy form. For example the electricity where the $CF_{elec,}$ is defined here as the ratio of standard primary energy to the useful work (electricity),

$$CF_{elec} = \frac{Q_{SPE}}{W_a} = \frac{T_{adia}}{\eta^{"}(T_{adia}-T_O)}. \qquad \text{(A7)}$$

Note that the equation A7 is thermodynamically meaningful as it is rooted both to corollary of the Second Law and anchored to the proposed common temperature platform. Irrespective of the designed temperature ratios at which the processes are designed or operated, any desalination process can be transformed to the common platform. Hence, the energy efficiency of all desalination methods could be compared justly where both quantitative and qualitative values of the input derived energy (electricity or thermal input) are accounted for in the framework.

<u>Heat driven desalination (Multi-effect distillation, **n**- stages)</u>

For the thermally-driven processes, such as the multi-effect distillation (MED), etc., no physical work output are produced except a finite rate of desalinated water production. Given the thermal heat input, Q_a, T_H and T_L of the MED method, the available Carnot work output (W_C) of the heat source can be determined using the heat engine approach. With the Carnot work and the same common primary energy platform, its corresponding standard primary energy (Q_{SPE}) is determined. As opposed to the work driven methods, the conversion factor (CF_{th}) is defined as the ratio of the standard primary energy consumption to the actual heat input supplied to the MED, i.e.,

$$(CF_{th}) = \left(\frac{Q_{SPE}}{Q_a}\right). \qquad \text{(A8)}$$

In summary, the thermodynamic framework provides the common energy platform that served two key roles: Firstly, the fractional apportionment of standardized primary energy consumption of cascaded processes of CCGT yields the suitable conversion factors for electricity (CF_{elec}) and thermal sources input (CF_{th}). Only the best conversion plants available hitherto are used for the calibration of such conversion factors. Secondly, the calibrated factors enable the reverse determination of the specific energy (Q_{SPE}) consumption. This determination is based entirely on the consumption of derived energy from the processes that consumed either electricity or thermal input. Consequently, the relative consumption of Q_{spe} from assorted desalination methods can now be compared meaningfully since these Q_{SPE} are all at a common energy platform.

Supplementary material 2

Based on a nominal fuel input of 2000 MW, the methodology of calculating the conversion factors, i.e., $CF_{electricity}$ and $CF_{thermal}$ are demonstrated below.

rocess	Properties/input	Calculation
Gas Turbines (GT)process	High temperature reservoir, T_H =1750K Low temperature reservoir, T_L =911K Ambient temperature reservoir, T_o =303K Input energy to CCGT, Q_H = 2000 MW	$W_{GT\_actual} = 768.87MW$ $W_{GT\_Catnot} = Q_H\left(1-\frac{T_L}{T_H}\right)$ $W_{GT\_Catnot} = 2000\left(1-\frac{911}{1750}\right) = 958.86mw$ $Q_{SPE\_GT} = \frac{W_{GT\_Catnot}}{\left(1-\frac{T_o}{T_H}\right)} = \frac{958.86}{\left(1-\frac{303}{1750}\right)}$ $= 1159.64\ MW$
Heat Recovery Steam Generator (HRSG:- air side)	High temperature reservoir, T_H =911K Low temperature reservoir, T_L =370K Product gad flow rate, m_{exh} =2002.5 kg/sec Cp_{exh}=1.055 kJ/kg.K	$Q_{HRSG\_airside} = \dot{m}_{exh} Cp_{exh}(T_H - T_L)$ $= 2002.5\ (1.055)(911-370)$ $= 1142.94\ MW$
Heat Recovery Steam Generator (HRSG:- steam side)	Effectiveness of HRSG, E_{HRSG} =0.862 Enthalpy of steam, $h_{833K,\ 113bar}$= 3514 kJ/kg Enthalpy of liquid, $h_{318K,\ 0.12bar}$= 189.0 kJ/kg	$\dot{m}_{steam} = \frac{(\ Q_{HRSG\_airside} E_{HRSG})}{h_{833K,113bar} - h_{323K,0.12bar}}$ $= \frac{(1142.94)\ (0.862)}{3514.0-189.0}$ $= 296.3\ kg/sec$
High Pressure (HP) Steam Turbines	Enthalpy of steam, $h_{833C,\ 113bar}$= 3514 kJ/kg Enthalpy of steam, $h_{683K,\ 28bar}$= 3360 kJ/kg	$W_{HP\_actual} = \dot{m}_{steam}\big(h_{833K,113bar}$ $- h_{683K,28bar}\big)$ $= 296.30\ (3514-3360)$ $= 45.63MW$
Medium Pressure (MP) Steam Turbines	Before thermal vapor compressor (TVC) bleed: Enthalpy of steam, $h_{833C,\ 28bar}$= 3600 kJ/kg Enthalpy of steam, $h_{768K,\ 17bar}$= 3490 kJ/kg	$W_{MP\_actual} = \dot{m}_{steam}\big(h_{833K,28bar}$ $- h_{768K,17bar}\big)$ $= 296.3\ (3600-3490)$ $= 32.60MW$

	After TVC bleed: Enthalpy of steam, $h_{768K,\ 17bar}$= 3490 kJ/kg Enthalpy of steam $h_{703K,\ 10bar}$= 3380 kJ/kg	$W_{MP\_actual} = \dot{m_{steam}}\left(h_{768K,17bar} - h_{703K,10bar}\right) = 288.3\ (3490 - 3380) = 31.71MW$
		$W_{MP\_actual\_total} = 32.60 + 31.71 = 64.31MW$
Low Pressure (LP) Steam Turbines	Before multi-effect distillation (MED) bleed: Enthalpy of steam, $h_{703K,\ 10bar}$= 3380 kJ/kg Enthalpy of steam, $h_{403K,\ 2.7bar}$= 2720 kJ/kg	$W_{LP\_actual} = \dot{m_{steam}}\left(h_{703K,10bar} - h_{403K,2.7bar}\right) = 288.3\ (3380 - 2720) = 190.28MW$
	After MED bleed: Enthalpy of steam, $h_{403K,\ 2.7bar}$= 2720 kJ/kg Enthalpy of liquid, $h_{319K,\ 0.1bar}$= 2590 kJ/kg	$W_{LP\_actual} = \dot{m_{steam}}\left(h_{703K,10bar} - h_{403K,2.7bar}\right) = 194.45\ (2720 - 2590) = 25.28MW$
		$W_{LP_{actual_{total}}} = 190.28 + 25.28 = 215.56MW$
Steam Turbines (ST)	HP_ST steam entry temperature, T_{H1} =833K LP_ST steam leaving temperature, T_{L1} =318K	$W_{ST\_actual\_total} = 45.63 + 64.31 + 215.56 = 325.5MW$ $W_{ST\_Catnot} = Q_{HRSG}\left(1 - \frac{T_{L1}}{T_{H1}}\right)$ $W_{ST\_Catnot} = 1142.94x0.862\left(1 - \frac{318}{833}\right) = 609.11\ MW$ $Q_{SPE\_ST} = \frac{W_{ST\_Catnot}}{\left(1 - \frac{T_o}{T_H}\right)} = \frac{609.11}{\left(1 - \frac{303}{1750}\right)} = 736.66\ MW$
$CF_{electrical}$		$CF_{electrical} = \frac{Q_{SPE\_GT} + Q_{SPE\_ST}}{(W_{actual\_GT} + W_{actual\_ST})} = \frac{1159.64 + 736.66}{(768.87 + 325.5)} = \mathbf{1.733}$

MED MED-TVC MSF MEDAD	In a heat-driven desalination plant, low pressure (LP) bled steam from LP-turbines is utilized as a heat source. Since MED, MED-TVC, HT-MED and MEDAD are operating at different temperatures, hence separate CF_{th} are calculated as shown below. MED-TVC: T_o=303K, T_H=403K MSF: T_o=303K, T_H=383K MED: T_o=303K, T_H=338K MEDAD: T_o=303K, T_H=333K	$CF_{th)} = \left(\frac{Q_{SPE}}{Q_a}\right) = \frac{\left(1-\frac{T_o}{T_H}\right)}{\left(1-\frac{T_o}{T_{adia}}\right)}$
$CF_{thermal}$	MED-TVC: T_o=303K, T_H=403K, corresponding CF_{th}=0.299 MSF: T_o=303K, T_H=383K, corresponding CF_{th}=0.252 MED: T_o=303K, T_H=338K, corresponding CF_{th}=0.125 MEDAD: T_o=303K, T_H=333K, corresponding CF_{th}=0.109	$CF_{th\text{-}MED} = \frac{\left(1-\frac{303}{338}\right)}{\left(1-\frac{303}{1750}\right)} = 0.125$