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Review of Thermal Desalination Plant Models Used in DEEP

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ABSTRACT

Desalination **E**conomic **E**valuation **P**rogram (DEEP) is a computer modelling software developed by the International Atomic Energy Agency (IAEA) related to economic evaluation of desalination systems combined with power generation. The program allows designers and decision makers to compare performance and cost estimates of various desalination and power plant configurations. Desalination options models include MSF, MED, RO and hybrid systems (MSF-RO, MED-RO) while power options include nuclear, fossil and renewable sources. The program also enables a side-by-side comparison of a number of design alternatives, which helps to identify the lowest cost options for water and power production at a specific location. This paper presents a review on thermal models of lost shaft work of the power plant due to steam extraction by MSF/MED desalination plants used in DEEP. Case studies results on economic evaluation of large scale hybrid MSF-RO coupled with PWR 600 MWe, PWR 900 MWe and CC 900 MWe power reactors using DEEP software for benchmarking are also presented. Overall improvement of DEEP performance has been discussed.

Introduction

A consultancy meeting on the Validation, Verification and Benchmarking of DEEP (Desalination Economic Evaluation Programme) was organized by NPTDS, IAEA at the VIC from 29 – 30 October 2007. The main objective of the Consultancy was to set out a work plan to benchmark and validate DEEP software. The following topics were discussed:

- Reference data currently available from nuclear real desalination plants as bases for validation process;
- Methods and means available to perform the DEEP validation;
- Evaluate the updating process and methodology of the currently available data, models, sub-programmes, and spread sheets of DEEP;
- Assign comparative case studies for benchmarking.

Another important objective was discussed to assess the most suitable approach and methodology to perform benchmarking of the software DEEP. Consequently DEEP have been reviewed/examined by many users, some have already pointed out some defects. Many improvements have been suggested particularly on thermal desalination plant models on DEEP such as:

- Introduction of proper calculation of lost shaft work
- Make a clear distinction in the code between extraction & back-pressure systems.
- Scrap the so-called minimum maximum brine temperature calculation.

To any designer or decision maker economic evaluation comes as later part of technical evaluation of a particular process. Once the technical part of the process is finalised and frozen, economic evaluation is done considering various alternatives. Fig 1 gives the various cost components of thermal desalination plant. Each of them contributes a significant portion to the cost of the water production. For thermal desalination plants energy cost contributes about 30-40% of the production cost. In a cogeneration plant amount of steam extracted for desalination is charged an equivalent amount of power loss of the power plant.

With this view, it was found that discrepancies in the calculation of lost shaft work model for various thermal models in DEEP. This paper discusses the irregularities and suggested modifications using different correlations to find out the exact lost shaft work. Further in the last technical meeting case studies work were assigned to large scale hybrid MSF-RO using PWR 600 MWe, PWR 900 MWe and CC 900 MWe. The results of these case studies are presented for benchmarking.

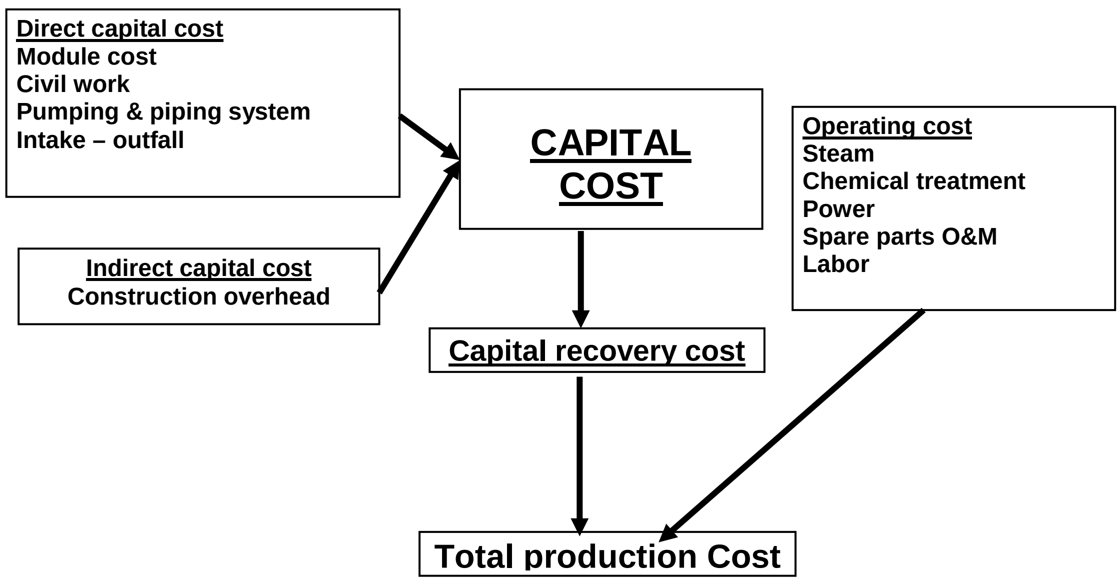


Fig. 1 Cost components of water production cost by a thermal desalination plants

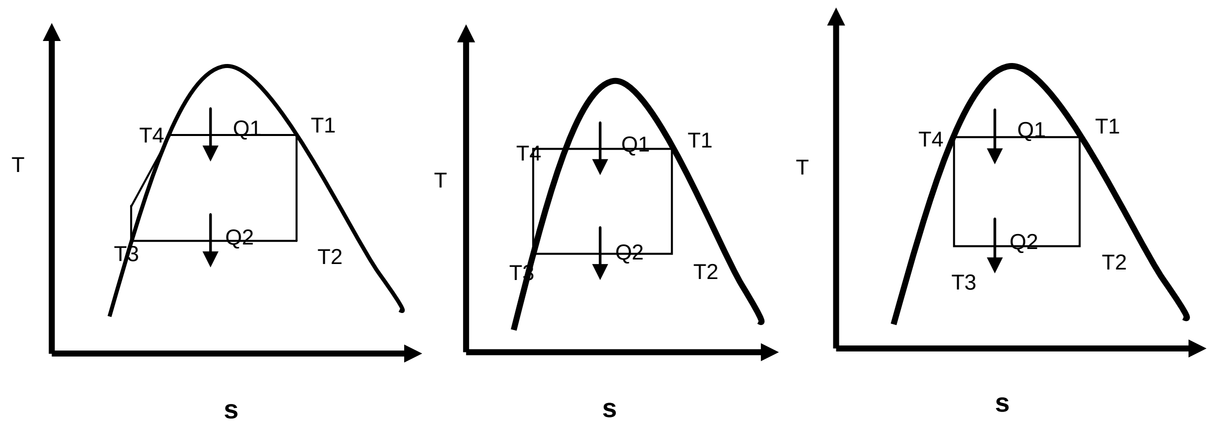
Lost shaft work Calculation (for extraction turbine): Assumption is that the extracted steam at saturated condition: <u>For NSC + MSF (MED) case</u>

1. **By Rankine Cycle Method**: The extracted steam used for desalination would have been used for power generation. Lost work is the difference of enthalpies (h1 – h2) between the enthalpy of saturated steam (h1) at extracted temperature (Tcm) and enthalpy (h2) at the site specific average condensing temperature (Tc) and is represented as DH (in MW) = ((h1 – h3)-(h2-h3))*Wdrc/Gor/24/860/4.186/1000 (where h1 and h2 is in kJ/kg, Wdrc is the water plant capacity in m^3/day. Therefore the lost shaft work (qls) is DH*hlpt, where hlpt is low pressure turbine efficiency. Here h1 is enthalpy of saturated vapor at Tcm but h2 is not the enthalpy of saturated vapour at condensing temperature. h2 is the enthalpy of expanded steam and water

mixture in the two phase region. How to find out those enthalpies a case study has been shown as below with typical example.

Let us consider NDDP (India MSF-RO project at Kalpakkam) case where steam is extracted from HP turbine exhaust with the following conditions: Reference diagram w.r.t. MSF NDDP case

- **Condition l . (Steam extraction)** Pressure (P1): 4.85 kg/cm^2, Temperature(T1) : 150^{o}C, Flow rate: @.22.0T/hr. This steam otherwise would have gone to condenser at condition 2.
- **Condition 2.** Same amount of steam is expanded to (P2):0.08 kg/cm^2, Temperature (T2): 45°C.



(a) Rankine Cycle **(b) Carnot 1 Cycle** **(c) Carnot 2 Cycle**

Fig. 2 Rankine and Carnot cycles

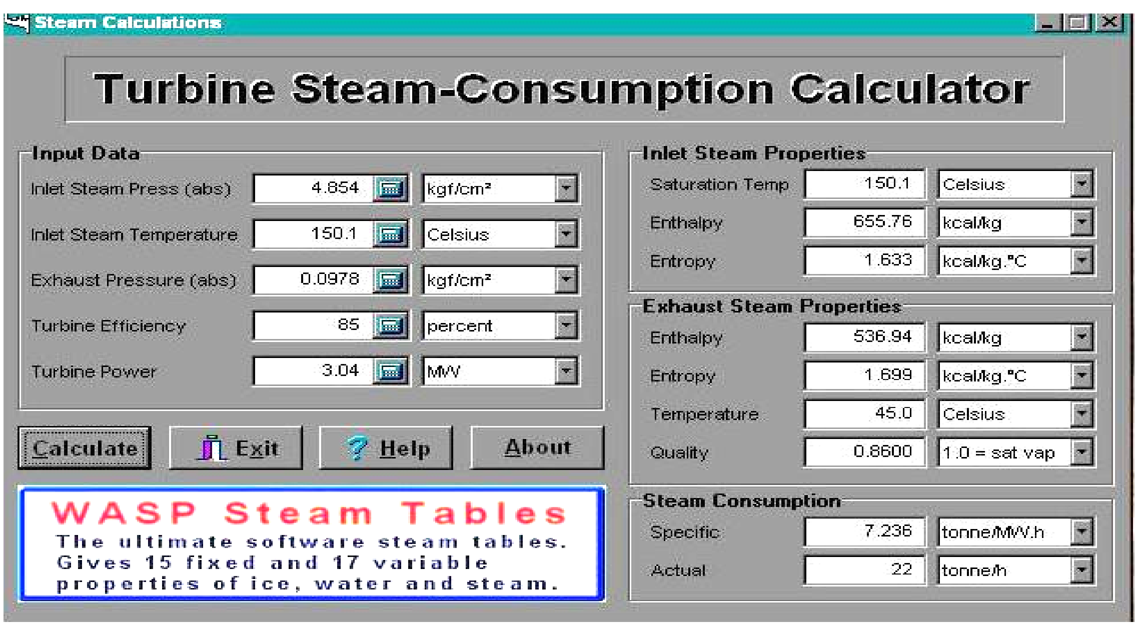
Fig.2 represents the Rankine and Carnot cycles. In the configuration (a) is the realistic Rankine cycle. Configurations (b) & (c) are the Carnot cycles at different modes. DEEP has used the simplest configuration (c) but it gives erroneous results as it uses latent heat as heat input and also heat rejection is also less. One point is to be noted that latent heat decreases as temperature of extraction goes up and vice versa. Attempt was made to keep same heat rejection as used by Rankine cycle, but it was seen that heat input was more and as a result more power is lost. This calculation procedure is tedious. In actual practice with considering Rankine, it seems that the procedure (a) is acceptable. Table 1 gives a comparative result of power loss calculation results by using various cycles.

Table 1 Comparative results of power loss of various cycles (case NDDP, India)

Parameter	**By Rankine Cycle (a)**	**By Carnot Cycle (b)**	**By Carnot Cycle (used by DEEP) (c)**
Heat added (Q1)	610.9 Kcal/kg	626.6 Kcal/kg	505.0 Kcal/kg (Latent heat)
Heat rejected (Q2)	**470.9 Kcal/kg**	**470.9 Kcal/kg**	379.8 Kcal/kg
Net work done (Q1-Q2)	140.0 Kcal/kg	155.7 Kcal/kg	125.2 Kcal/kg
Cycle efficiency (Q1-Q2)/Q1	0.229	0.248	0.248
Power Production	3.04 MWe	3.38 MWe	2.72 MWe
Eqv. loss power for desalination	3.04 MWe	3.38 MWe	2.72 MWe

A software output calculation was also shown in Table 3 to confirm the above results.

Table 3 Sample Power Calculation of NDDP by using software package



In DEEP Tcm is $5^{O}C$ more than the top brine temperature (Tmb).

Considering, final steam condensing temperature, T2=Tc (as used by DEEP). With thermodynamic considerations:

X2= (S1-S2l) /(S2g -S2l), Where X2 is the dryness factor of vapor at T2 condition and S is the entropy. So, enthalpy at T2 , h2= h2l + X2(h2g - h2l)

To find out entropies following correlations may be used:

For saturated vapour Sg = Function of saturated Temp at that pressure (available in the literature), For saturated liquid, Sl = Function of saturated temperature (literature)

To find out enthalpies following correlations may be used as

For saturated vapour hg = $2500.152+1.947036* Tg – 1.945387*10^{-3} *Tg^{2}$

For saturated liquid, hl = $0.5802129 + 4.151904 * Tc + 3.536659*10^{-4} *Tc^{2}$

Discussion with MED with Thermocompression

Table 2

Temperature increase in feedwater preheater	^{o}C	dTph	4.00
Average boiling point elevation	^{o}C	dTbe	0.393
GOR(new) according Rautenbach, p. 46/45 of the manual		GORnew	**8.00**
Calculation with Thermal Vapor Compression		TVC	**Y**
Optional Rtvc (see below)		Rtvco	0.00
DEEP default of Rtvc (see below)		Rtvcd	1.00
Ratio of entrained vapour flow to motive steam flow		Rtvc	1.00
Optional G.O.R.		Goro	0.00
G.O.R. as calculated by DEEP		GorD	16.00
Gained output ratio (kg product/kg steam)		Gor	**16.00**
Power-to-Heat Ratio		Rpth	3.4

Overall Plant Thermal Utilization	%	Eopth	37.4
Total heat to water plant	MW(t)	Qcrm	168.4
Turbine type: "BackPr" - backpressure or "ExtrCon" - extraction/condensing		TurType	ExtrCon
Low Pressure turbine isentropic efficiency		hlpt	0.850
Carnot efficiency		hcar	0.073
Combined turbine efficiency		h	0.062
Lost shaftwork	MW(s)	qls	**10.4**
Lost electricity production	MW(e)	Qle	10.0
Net electricity produced	MW(e)	Qnep	590.0
Flash steam flow to MED (water to MSF)	kg/s	Ffs	72.3

Normally, in DEEP steam extraction temperature is $5^{O}C$ more than the top brine temperature (Tmb). Lost shaft work is calculated as stated previously. But, when a thermocompressor is used for MED, GOR increases. This is due to use or extraction of high pressure steam. This steam is used as motive steam for thermocompressor. As stated in DEEP manual

"For the case of thermal vapour compression units coupled to MED or MSF systems, the GOR model is generalized as: GORtvc = GOR*(1+Rtvc)

Where, Rtvc is defined as the ratio of entrained vapour flow to motive steam flow,an input design parameter. The top brine temperature Tmb is also retained as a design parameter and as such can be an input by the user." For MED TVC case in the excel sheet cell =IF(TVC="Y", GORnew * (1+Rtvc), where, Rtvc is the Ratio of entrained vapour flow to motive steam flow. DEEP straightaway putting the value as default as Rtvc=1 else user have to put Rtvco value and can be used to calculate new GOR.

Suggestion: Instead of putting an input, Rtvc can be calculated as a function of pressures of suction (P_L), discharge ($P_{D)}$ and motive fluid (P_M) . The correlation (Ref: Hand book of evaporation technology by Paul E. Minton 1986 (London) Chapter 18 page 180) is as follows:

$$Rtvc = 1/ [0.4*e^{4.6 *\ln(PD/ PL)/ \ln(PM/ PL)}]$$

Here

P_L is function of suction or load temperature (Tc)

P_D is function of TC discharge temperature (Tcm)

P_M is function of motive steam extraction temperature (T_M). This is in the range of 5-10 bar. And P_M should be an input to the program and Lost shaft power calculation should be based on the high pressure steam extraction temperature and definitely it will be more than DEEP as on today.

DEEP Observations

- **Base cost:** The base plant cost (in $/m3/day) whatever is taken in the main sheet is the input and shown as output. However the actual construction cost is more than the base cost and that is not reflecting in the output. The total investment (construction cost(187 row) +IDC) should be given in the output based on as per row no. 221 in "Calc" section

- **Input**: In the main sheet only interest rate is input not the Discount rate. Only discount rate can be changed from "Calc" section. Users may not know these places. Again in input sheet on RO Plant Cost Data the row for Plant availability should be changed to plant construction lead time as shown in Table 4

Table 4 Input section

RO PLANT COST DATA

RO plant base unit cost	$/(m^3/d)	Cmu	**900**
Infall/outfall cost (% of construction cost)	%	Csmo	**7**
Plant cost contingency factor		kmc	**0.10**
Plant owners cost factor		kmo	**0.05**
Plant availability (if 0, value is calculated)		Lmo	**-1**
The above row should be "Plant construction lead time	(if 0,	value	**is calculated"**

- **Output**: Output sheet shows only interest rate. The discount rate is not shown.

- At Distillation plant performance section row 146: When NSC+MSF is chosen as coupled desalination unit "Average temperature drop between (MED)" should be replaced with MED/MSF or only MSF in case of only MSF. Row no. 140 it should be MED/MSF not RO when NSC+MSF is chosen.

- At “distillation plant performance input data section”: row no. 103. Brine to seawater temperature difference in last MSF stages when NSC+MED is chosen. It should be replaced with MSF/MED.

- For NSC+MSF case : No. of MSF recovery stages (row no.137) should be replaced with “Total No. of MSF stages”. Row no. 131. Flash steam (ffs) flow to MED(water to MSF) and same at row no. 292 (water to MSF). “Water to MSF” should be deleted. At line no. 130 Calculated number of RO unit should be replaced by **Calculated number of MSF(or MED) units**

DEEP Benchmarking

The following points have been considered for Hybrid (MSF-RO) plant bench marking using PWR 600 MWe, PWR 900 MWe and CC 900 MWe.

Table 3

Parameter			Value/Description
Power source			PWR 600 MWe, PWR 900 MWe and CC 900 MWe
Desalting capacities of hybrid plants in m^3/day			MSF-RO (4500/1800) MSF-RO (50000/25000) MSF-RO (200000/100000)
Seawater temperature (Tsw/Tsm/Tsd/Tsdo/Tsmo)			25 ^oC
Feed/Seawater salinity			35000 ppm
Interest &Discount rate	%/a	ir & I	8.00
Currency reference year		Ycr	2008
Initial construction date		Ycd	2009
Initial year of operation		Yi	2011 (for CC 900 2015)
Interest (ir)and discount rate (i)			8%
Specific construction cost			MSF Plant- 1000$/m^3$RO Plant- 900 $/m^3$
Purchased electricity cost			0.05 $/kWh
Carbon and Transportation cost			N/A
Steam extraction			Extraction turbine
Plant construction lead time			MSF (Ldo=-1), RO(Lmo=-1)
Default unit Capacity			10000 m^3/day

Benchmarking results

Case 1. CC 900 6300

Summary of Performance and Cost Results

Main Input Parameters

Project	**My Site**			**Case**	
Power Plant Data			**Water Plant Data**		
Type	CC		Type	MSF-RO	
Ref. Thermal Power	1,523	MW	Required capacity	6,300	m^3/d
Ref. Net Electric Power	900	MW	Hybrid Dist. Capacity	4,500	m^3/d
Construction Cost	685	$ / kW	Dist. Construction Cost	1,000	$ / (m^3/d)
Fuel Cost	100	$/BOE	Maximum Brine Temp.	110.0	°C
Purchased Electricity Cost	0.05	$/kWh	Heating Steam Temp.	0.0	°C
Interest Rate	8	%	Dist. Feed Temp.	25	°C
			Seawater Feed Salinity	35000.0	ppm
Configuration Switches			Hybrid RO Capacity	1,800	m^3/d
Steam Source	ExtrCon		RO Construction Cost	900	m^3/d
Intermediate Loop	N/A		RO Recovery Ratio	0.00	
TVC Option	N		RO Energy Recovery Fraction	0.95	
Backup Heat	N		RO Design Flux	13.6	l / (m^2 hour)
			RO Feed Temp.	25.0	°C
Water Transport					
Distance	0	km	**Carbon Tax**		
Pipeline System Construction Cost	0	M$ / km	Specific Carbon Tax	0	$ / ton
Pumping Power	0	MWe	Specific CO2e Emission	0	tons / MWh
O&M Cost	0	% of scc			

Performance Results

Lost Electricity Production	2.0	MW	Power-to-Heat Ratio	72.9	MWe/MWt
Plant Thermal Utilization	59.7	%			
Distillation Performance			**RO Performance**		
# of Effects/Stages	30				
GOR	9.4		Recovery Ratio	0.42	
Temperature Range	75	°C	Permeate Flow	1,800	m^3/d
Distillate Flow	4,500	m^3/d	Feed Flow	4,320	m^3/d
Feed Flow	9,000	m^3/d	Feed Pressure	60.1	bar
Steam Flow	5.56	kg / s	Product Quality	243	ppm
Brine Flow	4,500	m^3/d	Brine Flow	2,520	m^3/d
Brine salinity	70,000	ppm	Brine Saliniy	60,000	ppm
Specific Heat Consumption	65.63	kWh / m^3	Specific Power Consumption	3.12	kWh / m^3

Cost Results

Specific Power Costs			**Specific Water Costs**		
Fixed charge	0.009	$ / kWh	Fixed charge	0.379	$ / m^3
Fuel cost	0.166	$ / kWh	Heat cost	1.371	$ / m^3
O&M cost	0.006	$ / kWh	Plant electricity cost	0.605	$ / m^3
Decommissioning cost	N/A	$ / kWh	Purchased electricity	0.001	$ / m^3
Total carbon cost	0	$/kWh	O&M cost	0.270	$ / m^3
Levelized Electricity Cost	**0.180**	$ / kWh	Water production cost	2.625	$/$m^3$
			Water transport cost	0.000	$/$m^3$
			Total Specific Water Cost	**2.625**	$ / m^3

Case 2. AP600 6300

Summary of Performance and Cost Results

Main Input Parameters

Project	**My Site**			**Case**	
Power Plant Data			**Water Plant Data**		
Type	NSC		Type	MSF-RO	
Ref. Thermal Power	1,849	MW	Required capacity	6,300	m^3/d
Ref. Net Electric Power	610	MW	Hybrid Dist. Capacity	4,500	m^3/d
Construction Cost	2,194	$ / kW	Dist. Construction Cost	1,000	$ / (m^3/d)
Fuel Cost	6	$/MWh	Maximum Brine Temp.	110.0	°C
Purchased Electricity Cost	0.05	$/kWh	Heating Steam Temp.	0.0	°C
Interest Rate	8	%	Dist. Feed Temp.	25	°C
			Seawater Feed Salinity	35000.0	ppm
Configuration Switches			Hybrid RO Capacity	1,800	m^3/d
Steam Source	ExtrCon		RO Construction Cost	900	m^3/d
Intermediate Loop	Y		RO Recovery Ratio	0.00	
TVC Option	N		RO Energy Recovery Fraction	0.95	
Backup Heat	N		RO Design Flux	13.6	l / (m^2 hour)
			RO Feed Temp.	25.0	°C
Water Transport					
Distance	0	km	**Carbon Tax**		
Pipeline System Construction Cost	0	M$ / km	Specific Carbon Tax	N/A	$ / ton
Pumping Power	0	MWe	Specific CO2e Emission	N/A	tons / MWh
O&M Cost	0	% of scc			

Performance Results

Lost Electricity Production	1.9	MW	Power-to-Heat Ratio	49.4	MWe/MWt
Plant Thermal Utilization	33.5	%			

Distillation Performance			**RO Performance**		
# of Effects/Stages	30				
GOR	9.4		Recovery Ratio	0.42	
Temperature Range	75	°C	Permeate Flow	1,800	m^3/d
Distillate Flow	4,500	m^3/d	Feed Flow	4,320	m^3/d
Feed Flow	9,000	m^3/d	Feed Pressure	60.1	bar
Steam Flow	5.56	kg / s	Product Quality	243	ppm
Brine Flow	4,500	m^3/d	Brine Flow	2,520	m^3/d
Brine salinity	70,000	ppm	Brine Saliniy	60,000	ppm
Specific Heat Consumption	65.63	kWh / m^3	Specific Power Consumption	3.12	kWh / m^3

Cost Results

Specific Power Costs			**Specific Water Costs**		
Fixed charge	0.027	$ / kWh	Fixed charge	0.418	$ / m^3
Fuel cost	0.006	$ / kWh	Heat cost	0.319	$ / m^3
O&M cost	0.011	$ / kWh	Plant electricity cost	0.153	$ / m^3
Decommissioning cost	0.000	$ / kWh	Purchased electricity	0.002	$ / m^3
Total carbon cost	N/A	$/kWh	O&M cost	0.276	$ / m^3
Levelized Electricity Cost	**0.044**	$ / kWh	Water production cost	1.167	$/$m^3$
			Water transport cost	0.000	$/$m^3$
			Total Specific Water Cost	**1.167**	$ / m^3

Case 3: PWR900 6300

Summary of Performance and Cost Results

Main Input Parameters

Project	**My Site**			**Case**	
Power Plant Data			**Water Plant Data**		
Type	NSC		Type	MSF-RO	
Ref. Thermal Power	2,881	MW	Required capacity	6,300	m^3/d
Ref. Net Electric Power	951	MW	Hybrid Dist. Capacity	4,500	m^3/d
Construction Cost	1,763	$ / kW	Dist. Construction Cost	1,000	$ / (m^3/d)
Fuel Cost	7	$/MWh	Maximum Brine Temp.	110.0	°C
Purchased Electricity Cost	0.05	$/kWh	Heating Steam Temp.	0.0	°C
Interest Rate	8	%	Dist. Feed Temp.	25	°C
			Seawater Feed Salinity	35000.0	ppm
Configuration Switches			Hybrid RO Capacity	1,800	m^3/d
Steam Source	ExtrCon		RO Construction Cost	900	m^3/d
Intermediate Loop	Y		RO Recovery Ratio	0.00	
TVC Option	N		RO Energy Recovery Fraction	0.95	
Backup Heat	N		RO Design Flux	13.6	l / (m^2 hour)
			RO Feed Temp.	25.0	°C
Water Transport					
Distance	0	km	**Carbon Tax**		
Pipeline System Construction Cost	0	M$ / km	Specific Carbon Tax	N/A	$ / ton
Pumping Power	0	MWe	Specific CO2e Emission	N/A	tons / MWh
O&M Cost	0	% of scc			

Performance Results

Lost Electricity Production	1.9	MW	Power-to-Heat Ratio	77.1	MWe/MWt
Plant Thermal Utilization	33.3	%			
Distillation Performance			**RO Performance**		
# of Effects/Stages	30				
GOR	9.4		Recovery Ratio	0.42	
Temperature Range	75	°C	Permeate Flow	1,800	m^3/d
Distillate Flow	4,500	m^3/d	Feed Flow	4,320	m^3/d
Feed Flow	9,000	m^3/d	Feed Pressure	60.1	bar
Steam Flow	5.56	kg / s	Product Quality	243	ppm
Brine Flow	4,500	m^3/d	Brine Flow	2,520	m^3/d
Brine salinity	70,000	ppm	Brine Saliniy	60,000	ppm
Specific Heat Consumption	65.63	kWh / m^3	Specific Power Consumption	3.12	kWh / m^3

Cost Results

Specific Power Costs			**Specific Water Costs**		
Fixed charge	0.022	$ / kWh	Fixed charge	0.418	$ / m^3
Fuel cost	0.007	$ / kWh	Heat cost	0.288	$ / m^3
O&M cost	0.010	$ / kWh	Plant electricity cost	0.138	$ / m^3
Decommissioning cost	0.000	$ / kWh	Purchased electricity	0.002	$ / m^3
Total carbon cost	N/A	$/kWh	O&M cost	0.276	$ / m^3
Levelized Electricity Cost	**0.040**	$ / kWh	Water production cost	1.122	$/$m^3$
			Water transport cost	0.000	$/$m^3$
			Total Specific Water Cost	**1.122**	$ / m^3

Case 4: CC 900 75000

Summary of Performance and Cost Results

Main Input Parameters

Project	**My Site**			**Case**	
Power Plant Data			**Water Plant Data**		
Type	CC		Type	MSF-RO	
Ref. Thermal Power	1,523	MW	Required capacity	75,000	m^3/d
Ref. Net Electric Power	900	MW	Hybrid Dist. Capacity	50,000	m^3/d
Construction Cost	685	$ / kW	Dist. Construction Cost	1,000	$ / (m^3/d)
Fuel Cost	1,000	$/BOE	Maximum Brine Temp.	110.0	°C
Purchased Electricity Cost	0.05	$/kWh	Heating Steam Temp.	0.0	°C
Interest Rate	8	%	Dist. Feed Temp.	25	°C
			Seawater Feed Salinity	35000.0	ppm
Configuration Switches			Hybrid RO Capacity	25,000	m^3/d
Steam Source	ExtrCon		RO Construction Cost	900	m^3/d
Intermediate Loop	N/A		RO Recovery Ratio	0.00	
TVC Option	N		RO Energy Recovery Fraction	0.95	
Backup Heat	N		RO Design Flux	13.6	l / (m^2 hour)
			RO Feed Temp.	25.0	°C
Water Transport					
Distance	0	km	**Carbon Tax**		
Pipeline System Construction Cost	0	M$ / km	Specific Carbon Tax	0	$ / ton
Pumping Power	0	MWe	Specific CO2e Emission	0	tons / MWh
O&M Cost	0	% of scc			

Performance Results

Lost Electricity Production	21.0	MW	Power-to-Heat Ratio	6.4	MWe/MWt
Plant Thermal Utilization	66.2	%			

Distillation Performance			**RO Performance**		
# of Effects/Stages	30				
GOR	9.4		Recovery Ratio	0.42	
Temperature Range	75	°C	Permeate Flow	30,000	m^3/d
Distillate Flow	50,000	m^3/d	Feed Flow	72,000	m^3/d
Feed Flow	100,000	m^3/d	Feed Pressure	60.1	bar
Steam Flow	61.73	kg / s	Product Quality	243	ppm
Brine Flow	50,000	m^3/d	Brine Flow	42,000	m^3/d
Brine salinity	70,000	ppm	Brine Saliniy	60,000	ppm
Specific Heat Consumption	65.63	kWh / m^3	Specific Power Consumption	3.12	kWh / m^3

Cost Results

Specific Power Costs			**Specific Water Costs**		
Fixed charge	0.007	$ / kWh	Fixed charge	0.319	$ / m^3
Fuel cost	1.566	$ / kWh	Heat cost	9.777	$ / m^3
O&M cost	0.006	$ / kWh	Plant electricity cost	5.241	$ / m^3
Decommissioning cost	N/A	$ / kWh	Purchased electricity	0.001	$ / m^3
Total carbon cost	0	$/kWh	O&M cost	0.142	$ / m^3
Levelized Electricity Cost	**1.578**	$ / kWh	Water production cost	15.480	$/$m^3$
			Water transport cost	0.000	$/$m^3$
			Total Specific Water Cost	**15.480**	$ / m^3

Case 5: AP600 75000

Summary of Performance and Cost Results

Main Input Parameters

Project	**My Site**			**Case**	
Power Plant Data			**Water Plant Data**		
Type	NSC		Type	MSF-RO	
Ref. Thermal Power	1,849	MW	Required capacity	75,000	m^3/d
Ref. Net Electric Power	610	MW	Hybrid Dist. Capacity	50,000	m^3/d
Construction Cost	2,194	$ / kW	Dist. Construction Cost	1,000	$ / (m^3/d)
Fuel Cost	6	$/MWh	Maximum Brine Temp.	110.0	°C
Purchased Electricity Cost	0.05	$/kWh	Heating Steam Temp.	0.0	°C
Interest Rate	8	%	Dist. Feed Temp.	25	°C
			Seawater Feed Salinity	35000.0	ppm
Configuration Switches			Hybrid RO Capacity	25,000	m^3/d
Steam Source	ExtrCon		RO Construction Cost	900	m^3/d
Intermediate Loop	Y		RO Recovery Ratio	0.00	
TVC Option	N		RO Energy Recovery Fraction	0.95	
Backup Heat	N		RO Design Flux	13.6	l / (m^2 hour)
			RO Feed Temp.	25.0	°C
Water Transport					
Distance	0	km	**Carbon Tax**		
Pipeline System Construction Cost	0	M$ / km	Specific Carbon Tax	N/A	$ / ton
Pumping Power	0	MWe	Specific CO2e Emission	N/A	tons / MWh
O&M Cost	0	% of scc			

Performance Results

Lost Electricity Production	21.5	MW	Power-to-Heat Ratio	4.2	MWe/MWt
Plant Thermal Utilization	38.8	%			

Distillation Performance			**RO Performance**		
# of Effects/Stages	30				
GOR	9.4		Recovery Ratio	0.42	
Temperature Range	75	°C	Permeate Flow	30,000	m^3/d
Distillate Flow	50,000	m^3/d	Feed Flow	72,000	m^3/d
Feed Flow	100,000	m^3/d	Feed Pressure	60.1	bar
Steam Flow	61.73	kg / s	Product Quality	243	ppm
Brine Flow	50,000	m^3/d	Brine Flow	42,000	m^3/d
Brine salinity	70,000	ppm	Brine Saliniy	60,000	ppm
Specific Heat Consumption	65.63	kWh / m^3	Specific Power Consumption	3.12	kWh / m^3

Cost Results

Specific Power Costs			**Specific Water Costs**		
Fixed charge	0.027	$ / kWh	Fixed charge	0.410	$ / m^3
Fuel cost	0.006	$ / kWh	Heat cost	0.276	$ / m^3
O&M cost	0.011	$ / kWh	Plant electricity cost	0.150	$ / m^3
Decommissioning cost	0.000	$ / kWh	Purchased electricity	0.003	$ / m^3
Total carbon cost	N/A	$/kWh	O&M cost	0.145	$ / m^3
Levelized Electricity Cost	**0.044**	$ / kWh	Water production cost	0.985	$/$m^3$
			Water transport cost	0.000	$/$m^3$
			Total Specific Water Cost	**0.985**	$ / m^3

Case 6: PWR900 75000

Summary of Performance and Cost Results

Main Input Parameters

Project	**My Site**			**Case**	
Power Plant Data			**Water Plant Data**		
Type	NSC		Type	MSF-RO	
Ref. Thermal Power	2,881	MW	Required capacity	75,000	m^3/d
Ref. Net Electric Power	951	MW	Hybrid Dist. Capacity	50,000	m^3/d
Construction Cost	1,763	$ / kW	Dist. Construction Cost	1,000	$\$ / (m^3/d)$
Fuel Cost	7	$/MWh	Maximum Brine Temp.	110.0	°C
Purchased Electricity Cost	0.05	$/kWh	Heating Steam Temp.	0.0	°C
Interest Rate	8	%	Dist. Feed Temp.	25	°C
			Seawater Feed Salinity	35000.0	ppm
Configuration Switches			Hybrid RO Capacity	25,000	m^3/d
Steam Source	ExtrCon		RO Construction Cost	900	m^3/d
Intermediate Loop	Y		RO Recovery Ratio	0.00	
TVC Option	N		RO Energy Recovery Fraction	0.95	
Backup Heat	N		RO Design Flux	13.6	$l / (m^2$ hour)
			RO Feed Temp.	25.0	°C
Water Transport					
Distance	0	km	**Carbon Tax**		
Pipeline System Construction Cost	0	M$ / km	Specific Carbon Tax	N/A	$ / ton
Pumping Power	0	MWe	Specific CO2e Emission	N/A	tons / MWh
O&M Cost	0	% of scc			

Performance Results

Lost Electricity Production	20.1	MW	Power-to-Heat Ratio	6.8	MWe/MWt
Plant Thermal Utilization	36.8	%			

Distillation Performance			**RO Performance**		
# of Effects/Stages	30				
GOR	9.4		Recovery Ratio	0.42	
Temperature Range	75	°C	Permeate Flow	30,000	m^3/d
Distillate Flow	50,000	m^3/d	Feed Flow	72,000	m^3/d
Feed Flow	100,000	m^3/d	Feed Pressure	60.1	bar
Steam Flow	61.73	kg / s	Product Quality	243	ppm
Brine Flow	50,000	m^3/d	Brine Flow	42,000	m^3/d
Brine salinity	70,000	ppm	Brine Saliniy	60,000	ppm
Specific Heat Consumption	65.63	kWh / m^3	Specific Power Consumption	3.12	kWh / m^3

Cost Results

Specific Power Costs			**Specific Water Costs**		
Fixed charge	0.022	\$ / kWh	Fixed charge	0.407	\$ / m^3
Fuel cost	0.007	\$ / kWh	Heat cost	0.233	\$ / m^3
O&M cost	0.010	\$ / kWh	Plant electricity cost	0.136	\$ / m^3
Decommissioning cost	0.000	\$ / kWh	Purchased electricity	0.003	\$ / m^3
Total carbon cost	N/A	\$/kWh	O&M cost	0.145	\$ / m^3
Levelized Electricity Cost	**0.040**	\$ / kWh	Water production cost	0.924	\$/m^3
			Water transport cost	0.000	\$/m^3
			Total Specific Water Cost	**0.924**	\$ / m^3

Table 5 Summary of Benchmarking Results

	Capacity (m^3/day)	Water cost(\$/m^3) PWR 900	Water cost(\$/m^3) AP 600	Water cost(\$/m^3) CC 900
1	**6300**	**1.122**	**1.167**	**2.625**
2	**75000**	**0.924**	**0.985**	**15.48**
3	**300000**	**0.947**	**1.009**	**16.746**