Evaluation of Water Cost from Seawater Desalination in Dual-Purpose Plants for Potable Water Production and Electricity

Narmine H. Aly

Desalination Lab., Nuclear Research Center
Atomic Energy Authority, Cairo, Egypt
P.O. Box 13759, Fax 00202 4620778

ABSTRACT

During the past ten years, there was a wide scale gross in using seawater desalination in Egypt to solve water shortage problem in the remote areas. Most of these units are located in the touristic sits and in some military and industrial locations. The cost of water produced by seawater desalination is the main factor affecting the usage of desalination technology, not only in Egypt but also in many other countries with limited resources of water. Research and development programs to improve desalination technology were carried out to enhance the performance of the desalination plants and reducing its cost in order to attain minimum water cost produced. As the demand for desalted water is usually associated with a similar demand for electricity in arid regions, dual purpose plants are built to provide electricity for direct consumption and process steam which is used as an energy source to the desalination plants that convert seawater into fresh water. This has great impact on reducing the cost of distilled water produced. In this paper, A cost analysis study has been carried out to estimate the capital and running costs for different desalination processes using steam cycle power plants as the source of energy in co-generation plants. An exergitic cost allocation method is used to determine the cost of water produced. A detailed cost analysis results for Multi-stage flash, Reverse Osmosis and Multi-effect evaporators desalination units in single and dual purpose plants are presented and compared.

INTRODUCTION

At the end of 95, seawater desalination capacity of about 13.6 million m^3/d had been installed or contracted worldwide. According to the world market projections, the demand of seawater desalination will continue to increase.

In Egypt, in spite of the availability of the Nile River, the trend of using desalination processes to touristic supply water demand for sites, industrial and agricultural locations is increasing. According to the IDA report [1] the total installed capacity of desalination plants in Egypt by the end of 1992 is 87,000 m3/d. Sea water desalination represents 40.5 % of the total. RO is the most used desalination process in Egypt, representing 48.1 % of the total capacity.

The demand for water is usually associated with a similar demand for electricity, many cogeneration plants were built to provide electricity for direct consumption and process steam which is used by desalination plant that convert seawater to fresh water. From the thermodynamics and economic point of view, these cogeneration plants are the more energy efficient means of fuel resource utilization. That is the reason for combining seawater desalination plant with power station in integrated coproduction plants (dual purpose plant) in which high pressure steam is used to produce electricity and low pressure exhaust steam from the turbine service as heat source for desalination process.

One of the major issues concerning the pricing of the water and electricity produced by dual-purpose plant is dependent on how the total expenses of the plant are allocated between water and electricity produced.

There has been multiplicity of methods and procedures for cost allocation between water and electricity production, moreover there is no single standard to determine the actual production cost of water and electricity and consequently provide a basis for pricing both of them.

In the present study, a cost allocation method based on exergy prorating are presented and applied for typical dual purpose plant comprising steam power plant and desalination unit of different types Multi Stage Flash (MSF), Multi Effect Distillation (MED), and Reverse Osmosis (RO).

COST ALLOCATION METHOD

For a single purpose plant dividing the production expenditure (capital, fuel, and operation and maintenance costs) by the annual production output can arrive at the unit production cost.

In dual-purpose plant that have two final product, water and electricity. The unit cost estimate for each product is more difficult. There are several approaches [2,3,4] used in the dual purpose each yielding a unit cost for water and electricity.

Cost allocation approach is one of these approaches in which the annual expenditure for the whole plant is allocated to both products. This approach can be split into two methods.

First, the credit method, it consists in attributing to one of the products as a priori value and obtaining the cost of the other by difference.

Second, the cost prorating method, consist in dividing the total production cost according to a given set of rules entailing in general a sharing of this benefit between the two products.

Various prorating methods are used for dividing the annual cost of dual purpose plant between the two products, such as:

- Prorating in the basis of the total costs of single purpose alternative plant.
- Prorating in the basis of power generated
- Prorating in the basis of available energy or exergy, this method is used in the present work to evaluate the water and electric unit cost, which are produced from dual-purpose plant.

Exergy

Exergy of a system is a measure of the value of energy; it is defined as the useful work obtainable in a reversible process in which the system is brought from a given state to a state of equilibrium with the environment [5].

At certain state, exergy of a steady flow stream may be expressed as

$$E = (H - T_0) - (H_0 - T_0 S_0)$$

Where,

H enthalpy of stream, kW.

S entropy, kW °K.

T temperature, °K

Subscript o refers to the standard environment (usually the ambient seawater). In a reversible process, the output work, which can be produced, is equal to the drop of exergy through the process. However in an actual process – irreversible- the actual work is less than the isentropic work by the amount defined as exergy loss. For a real process,

$$E_{losses} = \left[1 - \frac{T_0}{T} Q_{in} \right] + E_{in} - E_{out} - W$$

Where,

E exergy, kW

W work, kW

The subscripts in, out denote the streams inlet and outlet of the process.

EXEGETIC COST ALLOCATION METHOD

The methods consists in breaking down the annual costs of the common sections of the dual purpose plants in proportion to the amount of exergy used to produce water and electricity respectively.

Exergy flow

Exergy of heat input by the fuel are split into three parts as follows:

$$E_{input} = E_e + E_c + E_s$$

Where,

E_e exergy flow to generate electricity.

E_s exergy flow of low pressure steam to desalination unit.

E_c exergy flow of common subsystems to produce steam and electricity.

Exergy flow to generate electricity includes:

- Net electrical output.
- Losses in the high pressure and low pressure turbine, condenser, and turbo generator.

Exergy flows of common subsystems to produce steam and to generate electricity are:

- Electrical auxiliary load.
- Exergy losses in the steam generator, feed water heaters, feed water pumps, and deaerator.

The exergy flow allocated totally to the generation of electricity E_E is equal to the exergy flow to generate electricity plus the share of generating electricity in the exergy flow of the common subsystems. This can be written as:

$$E_E = E_e + E_c \frac{E_e}{E_e + E_s}$$

Similarly the exergy flow allocated to generate steam can be written as

$$E_S = E_s + E_c \frac{E_s}{E_e + E_s}$$

COST ALLOCATION METHOD

In this method the capital and operating costs for each component are charged directly to the product produced by that component.

The low pressure and high-pressure turbine, condenser and generator expenses are allocated to the generation of electrical power since the main purpose of these components is to produce mechanical power or electricity.

Expenses of all other components of the power plant, i.e., steam generator, deaerator, feed water pump, and feed water heaters are apportioned between electricity and steam according to the exergy carried by each stream.

The expenses of the desalination plant are allocated totally to the production of water.

The total expenditure for the generation of electricity are arrived at by summing up the capital and operating costs C_E of the low-pressure turbine, high-pressure turbine, generator and a portion of the total expenses C_C of the other components of the system. This portion is the ratio between the exergy flow allocated the generation of electricity and the exergy flow input to the plant.

As the desalination unit consumes a part of the net power generated, then, the total expenses of producing electricity C_{ET} can be written as;

$$C_{ET} = \left[C_E + C_C \frac{E_E}{E_{input}} \right] \frac{P_{net} - P_{des}}{P_{net}}$$

Where,

P_{net} net power from turbo-generator

P_{des} power consumed by the desalination unit

Similarly the total expenditure to produce water C_{WT} are arrived at by summing up the cost of the desalination unit C_W, the cost of electricity consumed by the desalination unit, and the share of common components expenses as follows;

$$C_{WT} = C_W + C_C \frac{E_S}{E_{input}} + \left[C_E + C_C \frac{E_E}{E_{input}} \right] \frac{P_{des}}{P_{net}}$$

CONFIGURATIONS CONSIDERED

The flow diagram of the dual-purpose plant considered in this study is shown in Figure 1.

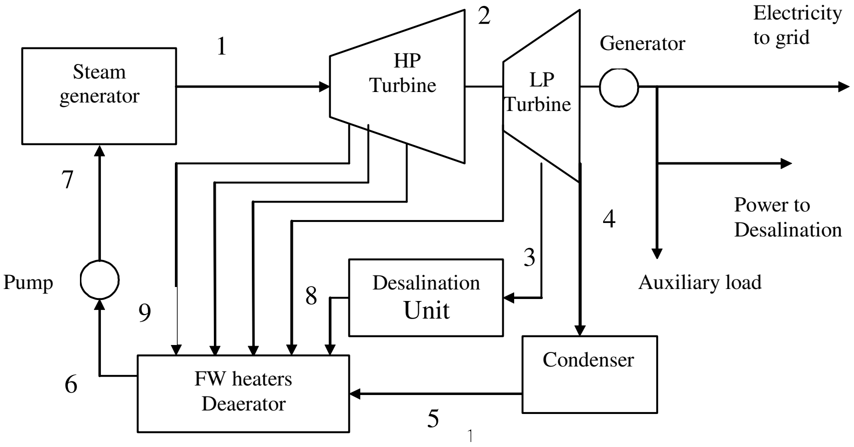

Figure 1 schematic diagram of duel purpose plant

The plant comprises a steam power plant of 80 MW rated capacity and desalination units with water capacity of 35,000 m^3/d.

Various seawater processes are considered in this study, all with the same water capacity, to be coupled with the power plant.

The desalination processes considered are Multi stage Flash (MSF), High Temperature and Low Temperature Multi Effect Distillation (HTMED, LTMED), and Reverse Osmosis (RO).

The steam is supplied to the turbine rated at 81.94 kg/s and throttle conditions of 60 bar, 485 °C. The turbine comprises high-pressure and low-pressure extraction sections. Five steam extraction points are provided in the turbine to supply steam to three feed water heaters, a deaerator, and the desalination unit.

The dual-purpose plant is assumed to be base load for both electricity and water.

The MSF unit is based on steam supply to the brine heater at 124 °C, while the LTMED and HTMED are based on steam supply to the evaporator at 124 °C, and 70 °C respectively. After allowing for pressure drop losses through the steam supply system and desalination plant inlet steam control valve, the pressure required at the brine extraction points is estimated as 2 bar, 132 °C for MSF, and 0.44 bar, 78 °C, 2 bar, 132 °C for LTMED and HTMED respectively.

The various options considered in the present study are:

Option 1: MSF unit with TBT 124 °C and Gain Output Ratio equal 11.

Option 2: MSF unit with TBT 90 °C and Gain Output Ratio equal 7.

Option 3: LTMED unit with TBT124 °C and Gain Output Ratio equal 21.

Option 4: HTMED unit with TBT 70 °C and Gain Output Ratio equal 11.

Option 5: RO unit

CAPITAL AND OPERATING COSTS

Capital costs for power and desalination plants considered are based on recent tender prices for similar co-generation plants [6,7,8]

The specific capital cost for steam power plant is taken to be $ 600 /MW.

For MED desalination unit, the capital cost is considered equal to $1440/ m^3/d for low temperature, $1680/$m^3$/d for high temperature evaporator, and $1350/$m^3$/d for RO unit.

Specific capital cost of MSF with capacities ranging from 30,000-45,000 m^3/d, Performance Ratio R = 6-11 is calculated from the following equation, [9]:

$$C_d = \left(360 + 1100 R^{0.658}\right)\left(\frac{D}{36360}\right)^{-0.7}$$

Annual amortization is calculated from the plant life time and discount rate as the inverse of the present worth equation;

$$Amortization = Capital\ \cos t \, \frac{r}{1+(1+r)^{-n}}$$

Where, n plant life times, y.

r discount rate

The desalination and power plant capital and operating costs are based on the following operating conditions:-

Power plant load factor	170%
Desalination unit load factor	85%
Plant life time	20 Year
Discounts rate	10% p.a.
RO membrane life	5 Years
Fuel cost	\$18 per barrel (\$2.8 per GJ)

The common items include civil works (building, foundation), seawater intake out fall, electrical switch gear, instrument and control system.

The running costs include, fuel, spare parts, chemical, and operating and maintenance costs.

The electrical power consumed by the desalination unit depends on its type of process, rated capacity, and performance ratio [10,11].

The operating and maintenance cost are taken to be equal to \$0.69/1000 gal for MSF, \$0.5/1000 gal for MED, and \$1.15/1000 gal for RO [8].

RESULTS AND DISCUSSION

The main technical parameters for the plant considered with the different desalination options are listed in Table 1.

Producing 35,000 m^3/d in a dual-purpose plant causes a decrease in the electrical power generated ranging from 13-24 MW according to the process used in the desalination unit.

Based on exergy flow and exergy loss equations, the exergy flow at the various nodes of the plant and the exergy loss in the different subsystems are listed in Tables 2 & 3 respectively for a dual purpose plant with MSF, TBT 124 °C, water capacity 35,000 m^3/d, and electrical rated power 80 MW.

Capital and operating costs for a dual purpose plant with various desalination options are listed in Table 4. The water cost varies between \$1.35 and \$1.21/m^3. As expected, for MED and MSF, the water production costs decreases either with the increasing performance ratio or with increasing TBT.

Figures 2 and 3 show water production cost and water cost breakdown produced by dual-purpose plant for various desalination process.

Table 1 Technical parameters for dual purpose plant

Options	1	2	3	4	5
Desalination plant					
Desalination process	MSF	MSF	HTMED	LTMED	RO
Maximum Brine Temperature, °C.	124	90	124	70	
Gain Output Ratio	11	7	21	11	
No. of stages/effects	33	19	28	14	
LP steam to desalination unit, kg/s	33.29	57.37	19.02	33.87	
pressure, bar	2	0.95	2	0.44	
temperature, °C.	132	98	132	78	
Enthalpy of steam to des., kJ/kg.	2,736	2,630	2,736	2,520	
Enthalpy of steam from des., kJ/kg.	505	411	505	327	
Desalination plant output, m^3/d.	35,000	35,000	35,000	35,000	35,000
Energy input to desalination, kW.	74,267	127,314	42,438	74,267	
Electrical power to des., kW.	4,812	5,687	1,750	3,354	8,750
Power plant					
Thermal energy input, MW.	233.0	233.0	233.0	233.0	233.0
Steam to turbine, kg/s.	81.94	81.94	81.94	81.94	81.94
pressure, bar	60	60	60	60	60
temperature, °C.	485	485	485	485	485
Steam to condenser, kg/s.	41.86	18.81	54.39	39.23	71.10
pressure, bar	0.066	0.066	0.066	0.066	0.066
temperature, °C.	38	38	38	38	38
Power from turbo generator, MW.	68.2	64.6	73.1	73.7	79.6
Power plant auxiliary load, MW.	3.4	3.2	3.7	3.7	4.0
Net electricity output, MW.	64.8	61.4	69.4	70.0	75.6
Power to grid, MW.	60.0	55.7	67.7	66.7	66.9

Table 2 Energy and Exergy flow

Node	Energy kW	Exergy kW
1	277,367	109,923
2	205,613	43,700
3	91,077	19,357
4	96,326	3,119
5	6,660	46
6	43,838	4,834
7	44,379	5,007
8	16,811	1,714
9	20,367	6,046

Table 3 Exergy loss, kW

	Option 1 MSF	Option 2 MSF	Option 3 HTMED	Option 4 LTMED	Option 5 RO
E input					
Exergy of fuel	140776	140776	140776	140776	140776
E_e					
Exergy losses in HP turbine	8790	10436	8712	11329	11167
Exergy losses in LP turbine	3014	959	3916	1412	2560
Exergy losses in condenser	3073	1381	3992	2880	5219
Exergy losses in turbine generator	1392	1318	1492	1505	1625
Net electrical output	64254	60834	68901	69495	75097
E_c					
Exergy losses in boiler	35861	35861	35861	35861	35861
Exergy losses in feed heaters	2972	2055	3797	3633	4899
Exergy losses in feed pump	369	369	369	369	369
Electrical auxiliary load	3410	3230	3655	3686	3981
E_s					
Exergy of steam to desalination unit	17643	24333	10082	10607	0
E_E					
Exergy flow to generate electricity	115517	106322	126184	125445	140776
E_S					
Exergy flow to generate steam	25259	34454	14592	15331	0

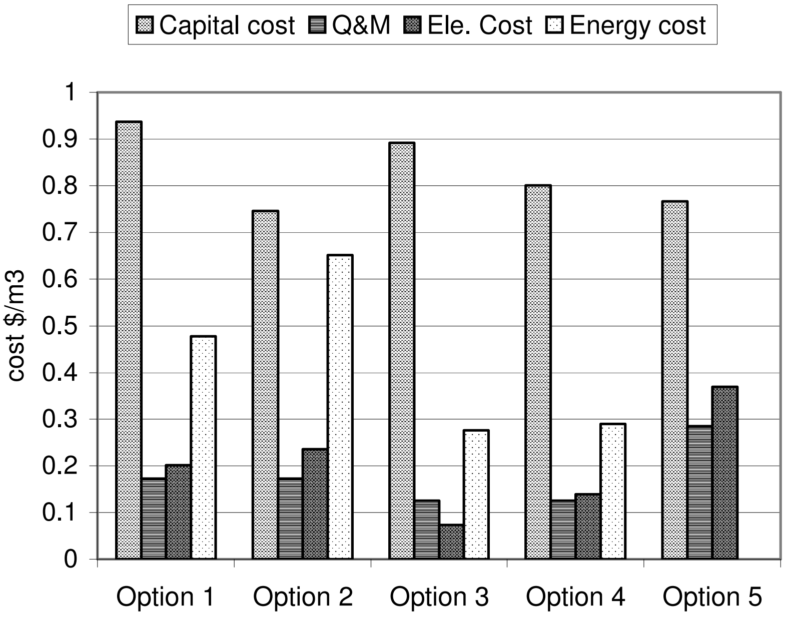

Figure 2 Breakdown water cost

Table 4 Capital & Running costs of dual purpose plants

Power Plant					
Capital cost, million $		48			
Levelized capital cost, million $/Y		5.63			
Variable O & M cost, million $/Y		1.02			
Fixed O & M cost, million $/Y		0.69			
Energy cost, million $/Y		24			
Foundation & building, million $/Y		3.28			
Desalination unit					
Options	**1**	**2**	**3**	**4**	**5**
Type	**MSF**	**MSF**	**MED**	**MED**	**RO**
Unit capital cost, million $	63.00	45.32	58.80	50.40	47.25
Seawater intake &outfall, million $	10.50	10.50	10.50	10.50	10.50
Backup heat source, million $	13.12	13.12	13.12	13.12	13.12
O & M cost, million $/Y	1.87	1.87	1.36	1.36	3.09
Total Expenses for producing electricity, m$/Y	27.27	25.02	30.85	29.99	30.64
Electricity Cost, $/kW hr	0.046	0.042	0.052	0.050	0.051
Total Expenses for producing water, million $/Y	19.42	19.60	14.83	14.71	15.43
Water cost, $/m^3	1.79	1.80	1.37	1.35	1.42

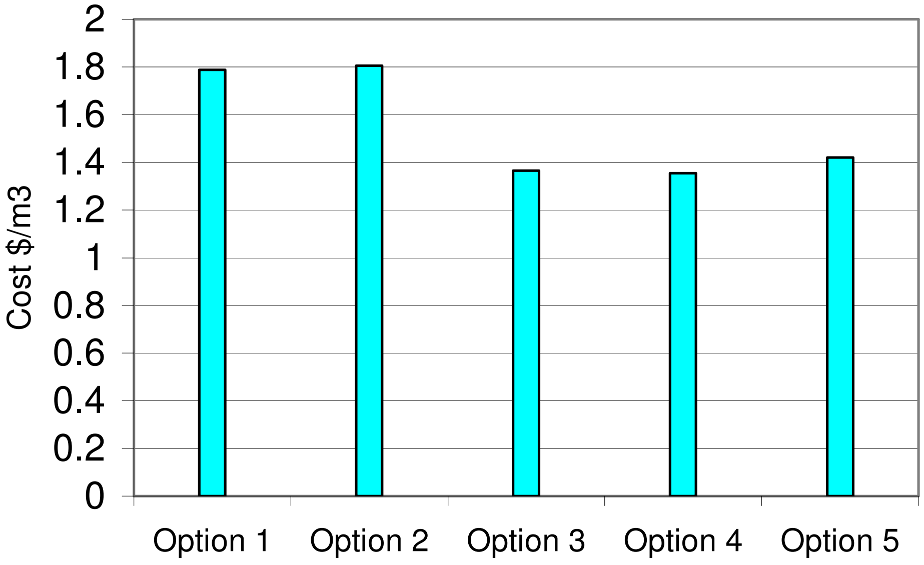

Figure 3 Water cost in dual purpose plant

Figure 4 gives a comparison between the cost of water produced by a dual-purpose plant and a single purpose desalination plant. It is shown that for all distillation processes coupled to steam power plan, the dual purpose plant for electricity and water production yield the lowest water production cost.

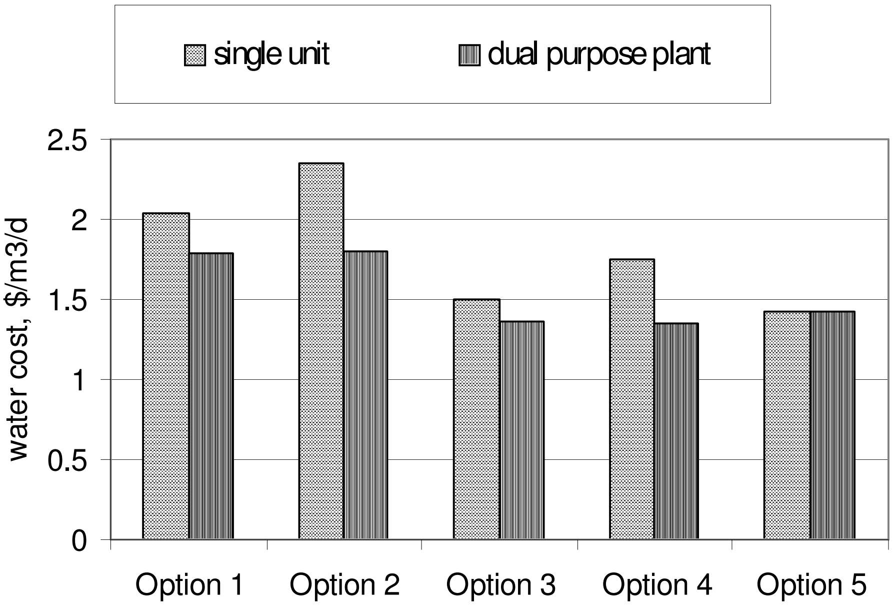

Figure 4 Water cost in single and dual purpose plant

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