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Research Article

Comparison between Reverse Osmosis Desalination Cost Estimation Trends

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Abstract Fresh water scarcity in many countries limits sustainable development; in many cases sea water desalination represents an ideal solution. Reverse osmosis membrane technology has developed over the past 50 years and it has 80% share in the total number of desalination plants installed worldwide. In this study, the approaches adopted for the economic evaluation of SWRO desalination processes, cost estimation programs and published equations that evaluate the capital and the total cost of desalinated water have been reviewed, analyzed and evaluated for further implementation of desalination plants. Four methods have been selected to simulate different desalination capacities. All costs have been updated using ENR cost index for 2015. The results show that for large capacities, the capital and unit costs are in accordance with a percent deviation when comparing different cost estimation procedure. WTCOST and DEEP software show comparable unit cost $0.96/m^3 and $0.99/m^3, respectively; while for capacities less than 1000 m^3/d there is a significant percent deviation between methods.

Keywords Desalination, Cost Estimation, Economics, SWRO

1. Introduction

Today, reverse osmosis membranes are the one of leading technologies for the desalination process, as they are applied to a diversity of salt water resources using membrane system design and tailored pretreatment. A wide variety of research and general information on RO desalination is available; however, a direct comparison of seawater and brackish water RO systems is necessary to highlight similarities and differences in process development [1]. One of the most critical features of any water treatment project is the cost. For membrane desalination, decreasing costs and producing higher water quality are among a number of important reasons why this technology continues. The cost of RO desalination plant is divided into direct capital cost, indirect capital cost and annual operating cost. Direct capital costs include the cost of land, major and auxiliary process equipment, and construction costs. Freight and insurance, construction overheads, and contingency costs are part of the indirect capital costs. While, annual operating costs are after plant commissioning and during plant operation and include chemicals, energy, wages, plant maintenance, expenditures etc. A wide distribution of these cost items are reported [2-3]. An exploratory study has been conducted to review the approaches adopted for the economic evaluation of SWRO desalination processes. Cost estimation programs that evaluate the capital and the total cost of desalinated water have been developed by several research and commercial entities. These water desalting cost programs enable estimation of desalting costs for sea water or brackish water using various technologies. Equations representing cost models have been developed by several authors. In addition, conceptual cost estimates for desalting process have been developed in graphical form [4].

1.1. Reported cost equations for membrane desalination plants

Several cost models have been presented by authors. These equations vary from detailed cost equations to short cut cost estimation equations that represent either total capital cost or unit cost of desalination [5-9]. Some of the reported cost equations for the essential components are presented below in Table 1.

Table 1: Reported cost equations for membrane desalination plants

Item	Equation	Reference
Capital Cost		
Intake/Outfall and pretreatment Cost	$Cip = 1.47 * 996 * (Qf)^{0.8} = 1417 * (Qf)^{0.8}$	5,6
Pumping and Energy Recovery System	$C_p = 0.0141 * (\frac{Wref * (101.32\,P)}{Rf})$	5,7
Booster Pump	$BoosterPump(\$) = (665970 * (DesignFlow)^2 - 13682 * (DesignFlow) + 829.1) * 1.033$	8
Membrane Cost	$Cm = Cmem * (\frac{Am}{Amod})$	5,7
Operating Cost		
Membrane Replacement Cost	$Crep = P_m * Y_r * \frac{\lambda}{V_1}$	9
Chemical Treatment Cost	$C_c = 8000 * \left(\frac{24\,Wp}{Qm.\rho}\right) * 0.2 \quad \$/yr$	5,7
Electricity	$W_{pump} = \sum \Delta P * \frac{V_{pump}}{\eta K}$	9
M and Spare Parts	2% of direct capital cost	9
Labor Cost	0.048*capital cost	10
Pressure Pump Operating Cost	$C_{op} = Pf * \left(\frac{Qf}{\eta}\right) * D_{energy} * PlantloadFactor$	6

An additional 20% was added for the cost of electrical and instrumentation systems associated with the inter-stage pumping were estimated based on vendor data and RS Means (Reed Construction Data) [8]. “Depreciation” is an important item in calculating the plant cost. There are two main methods of calculating depreciation: “Prime Cost”, “Straight Line” or “Fixed Installment” method, and “Diminishing Value or Reducing Balance” method. "Prime Cost" gives a constant charge from year to year, whilst "Diminishing Value" decreases from year to year so that the earlier years bear a larger allocation of the asset's cost [11].

1.2. Abridged Cost Estimation Equations

Different authors present abridged equations to estimate capital and operating costs of seawater desalination using RO estimates the total capital using the permeate selling cost, membrane cost and pumps cost [12].
The capital cost of contracting according to (ESCWA, 2002) [13] is:

$$\boldsymbol{C = 1403.38 * (Qp)^{0.8539} Euro} \qquad \textbf{(1)}$$

Another short cut cost estimating equation is presented by (Lamei et al., 2008) [14] as:

$$\boldsymbol{C_p = 6.25 * Q^{-0.17}} \qquad \textbf{(2)}$$

The unit cost of desalination varies for different types of feed water salinity and is a function of many factors such as plant capacity, feed water quality, pretreatment needed, desalination process and technology, energy cost, plant life, and amortization of capital investment. In general, the unit cost of desalted water is inversely proportional to the plant size (economy of scale) i.e. if all other factors remain the same, the cost of product water would be lower for bigger plants [15].RO desalination plants are available in much bigger sizes, where large plants were mainly Thermal Desalination; MSF, MED and VC in the past with increased productivity (an increase of 94% from 1990 to 2002) and better membrane material to handle more operating pressure.

1.3. Cost Estimation Software for membrane desalination

Desalination economic evaluation program software’s have been developed to estimate the costs of desalination for strategic investments. In 2008 Leitner developed “The seawater desalting costs program” which calculates design parameters such as heat transfer surface area required for MSF, MED and TC/MED and number of membranes modules for seawater [17]. Other interactive programs have been developed e.g. DEEP and WTCOST [18-19].

1.3.1. DEEP Code

Desalination Economic Evaluation Program, DEEP developed by International Atomic Energy Agency (IAEA) and issued in 1989, which is useful for preliminary economic evaluation for different combinations of various energy sources of fossil and nuclear power plants with different desalination processes (MSF, MED, RO and possible hybrid combinations) (IAEA, 2000). This package is continuously updated [19].

1.3.2. WT-Cost Program

WT-COST is a well-known commercial computer software program, developed by the "US Bureau of Reclamation and Moch & Associates" for evaluation and comparison of water treatment processes that employ reverse osmosis/nanofiltration, electro-dialysis, microfiltration/ultrafiltration, and ion exchange. It uses flexible cost indices and adjustable inputs and includes cost equations for estimating different pre and post-treatment costs. Unit operations include media filtration; coagulation and flocculation with powdered activated carbon, alum, ferric chloride, ferrous sulfate, or polyelectrolyte; disinfection by chlorine, mono-chloramine, ozone, and ultraviolet light; lime/soda softening; electrical operations including energy recovery; and chemical consumptions and intake and outfall infrastructures [18].

1.3.3. Other cost software includes

ROSA (Reverse Osmosis System Analysis) design software to aid in system design using DOW FILMTEC™ elements [20].

1.4. Seawater RO Desalination Cost Estimation Graphs

Compiled operations and maintenance costs for desalination plants over the same range of product water flow presented in Figures, for estimating the construction costs at the preliminary design level for water treatment processes and complete plants [4].

1.5. Additional costs

Main additional costs for the desalination plant is addressed to environmental protection, particularly brine disposal. There are other additional costs including but not limited to distribution and of losses in the storage or distribution network. Typical cost of desalted water reported is the combination of investment, capital, and O & M costs, generally there are no attempts to include the costs of environmental protection or water distribution.

1.6. Published/Reported Costs

Another method of determining the cost of a desalination plant is comparing the required plant capacity to another published capacity/cost. By applying correcting equipment cost for inflation At any rate, the equation expresses the rule of six-tenths[21] using updated cost index e.g. ENR or Marshal and Swift cost index, results when only an approximate cost within plus or minus 20% is expected.

$$C_2 = C_1 * \left(\frac{Q2}{Q1}\right)^{0.6} \qquad \textbf{(3)}$$

Cost indices are useful when basing the approximated cost on other than current prices. This cost must be multiplied by the ratio of the present day index to the base index in order to proportion the value to present day currency.

$$C_2 = C_1 * \left(\frac{Q2}{Q1}\right) \qquad \textbf{(4)}$$

This work is dedicated to cost analysis of seawater desalination plants. Capital, operating costs and unit production costs of the systems were analyzed and evaluated using different methods.

2. Case Study Approach and Methodology

In order to estimate the water production cost of RO plant before it is constructed it is essential to know the similar plants cost constructed around the world. Taking into consideration when estimating the plant cost; the local conditions and the factors affecting the unit cost of water. The costs for the proposed capacities of 1000, 50,000 and 100,000 m^3/d have been evaluated using different methods:

- Rigorous Cost Model: WT-Cost
- Rigorous Cost Model: DEEP code
- Equation by Lamei et al., 2008

$$C = 1340.9e^{-2*10^{-5Q}} \qquad \textbf{(i)}$$

$$C_p = 6.25* Q^{-0.17} \qquad \textbf{(ii)}$$

A developed empirical correlation by the author [16] for desalination capacities over 25000 m^3/d.

$$C = \left(e^{-8(Q^3)}\right) - (0.01 * Q^2) + \left(3337.2 * (2Q)\right) - (5e^7)\textbf{(iii)}$$

Comparing the results with actual plant cost as Perth seawater reverse osmosis plant with a capacity of 250,000 m^3/day was contracted with total project cost AUS$ 387 million in 2009, in Bahrain, a plant capacity of 80,200 m^3/day with a total of $ 111 million. The comparison provides practical understanding of knowing the difference and deviation from actual plant costs [22].

3. Results and Discussion

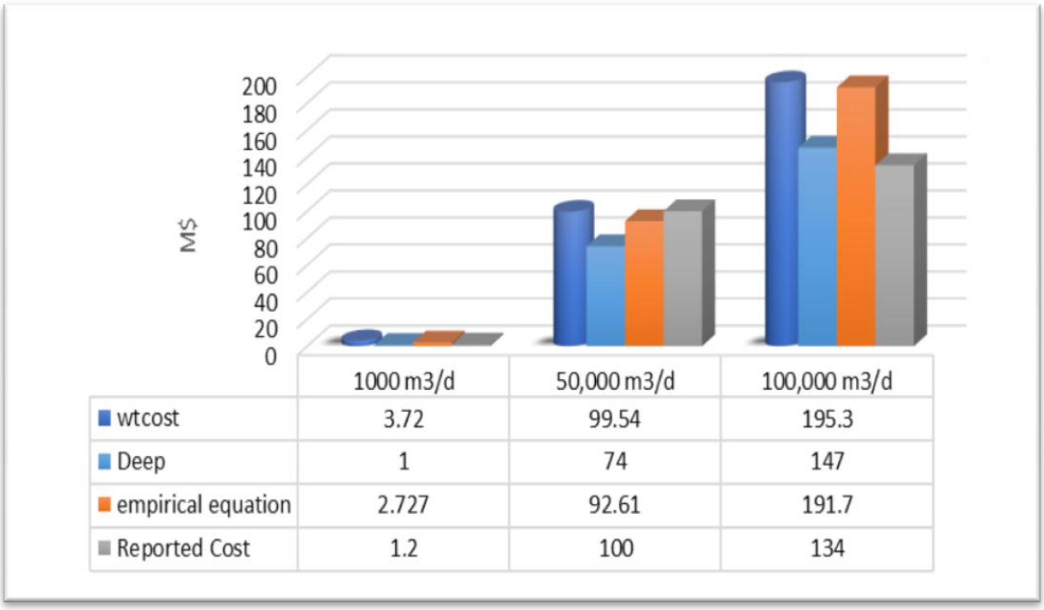
For both WT-COST and DEEP intake and outfall items have been calculated. The recovery of the desalination plant was estimated to be 40%. Comparing the results to get with an accurate costing method is a difficult task as desalination costing is very site specific and so many parameters are taken into consideration e.g. energy costs, discount rates, etc.

Table 2: Comparison between different methods for different capacities

Method	Capital Cost, M$	O&M, M$/yr.	Unit cost, $/m^3$
For 1000 m^3/d desalination plant			
WT-COST	3.72	0.88	2.5
DEEP	1	0.61	1.86
Abridged method			1.9
Empirical equation			
Updated cost using ENR cost index	2,727	--	--
Reported Cost*1	1.2	-	1.6
For 50,000 m^3/d desalination plant			
WT-COST	99,540	17,060	1.04
DEEP	74	20.16	1.228
Abridged method	--*	--	0.99
Empirical equation			
Updated cost using ENR cost index	92,610	--	--
Reported Cost*	100	-	-
For 100,000 m^3/d desalination plant			
WT-COST	195.300	31.56	0.96
DEEP	147	32.75	0.997
Abridged method	181*	--	0.889
Empirical equation			
Updated cost using ENR cost index	191,720	--	--
Reported Cost*	126-134	-	0.95-1.14

equation validity for capacity higher than 80,000m^3/d[23-25]

The results presented in Table 2 and Figure 1; shows that for large capacities the capital and unit costs are in accordance by comparing different cost estimation procedure. WT-Cost software and DEEP show equivalent unit cost with a slight deviation $0.96/$m^3$ and $0.99/$m^3$ while for capacities less than 1000 m^3/d there is a percent deviation between methods. The variation in cost estimation is due to the involvements of many variables such as membrane costs, energy costs, interest rates, discount rates, feed pressure, flow rate etc. which affect the unit cost of water produced. However, the variables used in cost analysis e.g. membrane costs, energy costs; interest rates etc., are random in nature, therefore making the total cost of water uncertain in nature.



	1000 m3/d	50,000 m3/d	100,000 m3/d
wtcost	3.72	99.54	195.3
Deep	1	74	147
empirical equation	2.727	92.61	191.7
Reported Cost	1.2	100	134

Figure 1: Capital Cost comparison between different methods

4. Conclusion

Desalination represents a possible alternative technology for the efficient production of water from saline water sources. As found through this study the desalination plant produces 100,000 m^3/day, the results show that the estimated unit cost is nearly corresponding with the published plants cost with similar capacities. A well as rigorous cost methods e.g. WT-Cost software and DEEP show equivalent unit cost with a slight deviation $0.96/$m^3$ and $0.99/$m^3$. The capital cost item shows a difference between the calculated and published cost data, which may be due to difference in design, local conditions and interest rates etc. Unit cost can be reduced by reducing labor costs via employing highly skilled operators and following the contracting maintenance duties Factors that contributed to RO cost reductions due to technological development are; lower membrane replacement costs, and fewer chemicals needed, alternative less manpower requirements because of process automation, and effective pretreatment of the feed water. Such data would enable identification of possibilities for cost management and for contract negotiation between companies and contractors in outsourcing management of desalination plant.

Nomenclature:

C_p	unit cost \$/m^3
Q	capacity m^3/day
Q_p	product water m^3/day
Q_f	the feed flow rate (m^3/day)
W_{ref}	Reference plant capacity of 29484 m^3/day
R_f	Recovery fraction
P	Operating pressure (KPa)
C_{mem}	module cost (\$)
A_m	membrane area required for RO plant (m^2)
A_{mod}	module membrane area (m^2)
P_m	membrane purchase cost (\$)
Yr	Years
λ	value between 0.05-0.2 depends on salinity and water quality

Vl	total value of water produced during life time (30 years)
C*c*	Chemical treatment cost $/yr
Q_m	module capacity m^3/day
W_p	permeate flow rate kg/hr
ρ	pure water density kg/m^3
W_{pump}	kW
ΔP	pressure increase kPa
V_{pump}	Flow rate m^3/s
ηk	Efficiency of the pump
Pip	outlet pressure 5*105 N/m^2
h	intake pump efficiency 0.74
D_{energy}	unit power cost

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