International Journal of Applied Research 2017; 3(8): 790-794

ISSN Print: 2394-7500
ISSN Online: 2394-5869
Impact Factor: 5.2
IJAR 2017; 3(8): 790-794
www.allresearchjournal.com
Received: 10-06-2017
Accepted: 15-07-2017

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Studies on solar thermal desalination

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Abstract
This paper presents an economic model capable of evaluating the economics of multi-stage flash desalination plant coupling with solar collectors. The results show diminishing specific discounted water production costs (SDWPC) with system scale and service lifetime and limited returns from using 20% more expensive and high–quality equipment that may mitigate are equal percentage maintenance costs and extend service life.

Keywords: Studies, solar thermal, SDWPC

Introduction
An indirect solar thermal seawater desalination system consists of a solar collector system and a distillation system. In order to achieve continuous operation, solar systems are coupled with thermal energy storage systems [1–5].
Distillation systems can utilize the stored low grade heat in order to drive the desalination process [2, 3]. This eliminates the need for electrical or mechanical energy. Thermal desalination systems can treat a wide range of water sources ranging from brackish to concentrated regimes. Desalination systems are necessary in order to meet growing demands for freshwater, coupling desalination systems with solar energy technologies is one possible route for eliminating the need for fossil fuel energy sources. This paper build a techno–economic model that assesses the viability of coupling solar collectors with thermal desalination systems. The model considers the impacts of system lifetime and scale, unit price and performance parameters for each subsystems

Formulation
The heat gains per day of a solar collector system at a given efficiency is calculated by "Hottel-Whillier-Bliss equation",

$$Q_u = AF_Rh[I\tau\alpha - U\,(T_{in} - T_a)] = \eta_c AIh \quad (1)$$

where A is the area of the solar collector, I is the average solar irradiance, F_R is the collector heat removal factor, τ is the transmissivity, α is the absorptivity, U is the heat dissipation coefficient of the collector, T_{in} is the temperature of the working fluid entering the collector, T_a is the ambient temperature, η_c is the average efficiency of the collector, and h is the daily working time of the solar collector. If the total solar irradiance value per day in unit area is H ($kWh/m^2/day$), then the average daily heat gains are:

$$Q_u = \eta_c \cdot H \cdot A \quad (2)$$

The annual water production Me (kg/year) of solar desalination plant is:

$$M_e = P_r \cdot D \cdot \frac{\eta_c \cdot H \cdot A + W}{h_{fg}} \quad (3)$$

where P_r is performance ratio, a measure of the energy consumed in desalination process, W is the power necessary to operate the auxiliary components like water pump, vacuum pump, control system etc., and D is the number of days the plant is operating in a year. The daily water production m_e (kg/day) is relevant to system scale x (m^3/day):

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$$m_e = \frac{M_e}{D} = \rho_w \cdot x \qquad (4)$$

where ρ_w is the density of water (approximated to be 1000 kg/m^3). Freshwater production scale is dependent on the direct needs of the region and available funds.

Investment analysis of solar desalination system

Solar thermal desalination systems comprise solar collectors, heat storage and piping, power supply and control systems, and a desalination subsystem (Fig. 1). Solar collectors collect sun's energy as a heat source. The thermal energy is either stored in the heat storage or supplied to seawater desalination system. The economics of the solar desalination is related to the construction costs associated with each subsystem. The water production cost for a solar seawater desalination plant decreases linearly as the scale of the plant increases exponentially (especially at scales ≫ 10 m^3/day). The construction cost for the solar collector system considering scale factor can be calculated as:

$$C_1 = x \cdot C_{1,0} (1 - b \cdot \log x) \qquad (5)$$

where $C_{1,0}$ ($/($m^3$/day)) is a normalized cost for a solar collector to produce 1m^3 of freshwater per day and b is the variation coefficient of the cost. The variation coefficient of the cost is a measure of decreasing cost for scale for a specific component or device. For instance, when b is 0.1, the cost decreases at a rate of 10% per unit area for every tenfold increase in plant scale. In reality, the cost variation coefficient for each subsystem is different. However, for simplicity, in this analysis we assume they are equal. The normalized cost for a solar collector is:

$$C_{1,0} = A_0 \cdot C_{sc} \qquad (6)$$

where C_{sc} ($/$m^2$) is the cost of solar collector per unit area, and A_0 (m^2/m^3/day) is the specific solar field area required to produce one m^3/day freshwater. The specific solar field area is derived from Eq. (3) and Eq. (4).

$$A_0 = \frac{\frac{\rho_w \cdot h_{fg}}{Pr_a}}{\eta_c H} \qquad (7)$$

where $W_0 \left(\frac{kWh}{m^2/day}\right)$ is the specific power consumption.

According to the same analysis method, the energy storage and piping construction costs are:

$$C_2 = x \cdot C_{2,0} (1 - b \cdot \log x) \qquad (8)$$

where, $C_{2,0}$ ($/($m^3$/day)) is the normalized construction cost of the energy storage and pipeline subsystem and can be calculated:

$$C_{2,0} = \eta_c H A_0 \cdot s \cdot c_2 \qquad (9)$$

where $\eta_c HA_0$ is the total energy collected by solar collector in a specific solar field area. Part of this energy is used directly for desalination and the other part is stored. Then s represents the ratio of stored energy to collected energy and c_2 ($/kWh) is the specific price of thermal energy storage.

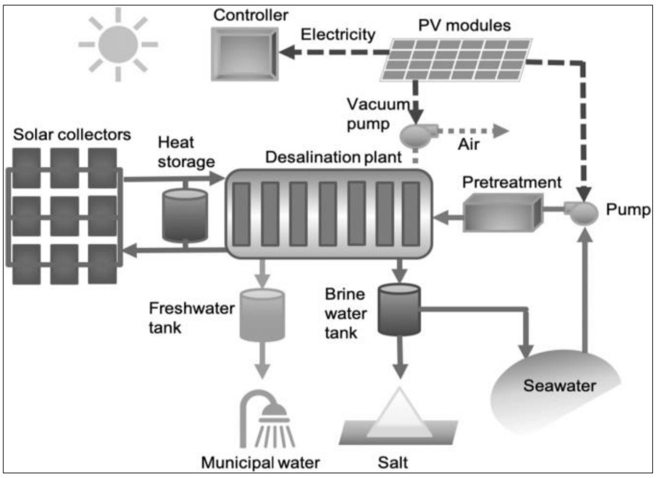

Fig 1: Overview of solar thermal desalination plant which shows economic considerations.

While thermal energy can be used directly to desalinate water in phase-change separation processes, there are numerous plant level considerations that require an additional electrical energy source. Auxiliary devices such as pumps and vacuums pumps all require electrical energy for operation. The electric power can be supplied by the utility power or with solar photovoltaic cells. The economics with energy source selection is governed by geographical and resource considerations. The economics of photovoltaic solar electricity production is related to the solar cell efficiency η_s. The specific area of solar photovoltaic cell A_e ($m^2/(m^3$/day)) can be calculated by:

$$A_e = \frac{W_0}{\eta_s H} \qquad (10)$$

The construction cost of power supply can be expressed by:

$$C_3 = x \cdot C_{3,0} (1 - b \cdot \log x) \qquad (11)$$

where $C_{3,0}$ ($/($m^3$/day)) is the normalized construction cost of the solar cells and can be calculated:

$$C_{3,0} = A_e \cdot C_e \qquad (12)$$

where C_e is the cost of solar cells per unit area. When the power of a solar desalination system is supplied by utility power, C_3 can be neglected. However, the operations and maintenance (O&M) costs will be increased as it takes into account electricity consumed.

When utility power supplies the electricity of the solar desalination system, electricity price is an important factor to consider. Assume unit electricity price is P_e ($/kWh), and the annual increase rate of electricity price is β, then the present discounted value of the cost of the electricity at the nth year can be written as:

$$C_{E,n} = \frac{xDW_0P_e}{(1+\gamma)^n}(1+\beta)^n \qquad (13)$$

Desalination subsystem and site preparation are two additional considerations when evaluating economy for solar desalination plants. The construction cost of the desalination system and related components can be expressed by:

$$C_4 = x \cdot C_{4,0}\ (1 - b \cdot \log x) \quad (14)$$

where, $C_{4,0}$ (\$/(m^3/day)) is the normalized construction costs of the desalination subsystem and related components. Since solar collectors and solar photovoltaic cells occupy a large footprint, their specific area can estimate the cost of site preparation. The normalized site preparation cost $C_{sp,0}$ (\$/(m^3/day)) is:

$$C_{sp,0} = csp \cdot Z \cdot (A_0 + A_e) \quad (15)$$

where c_{sp} is the site preparation cost per unit area (\$/m^2) and Z is the ratio of the footprint of the entire plant to the footprint of the solar device. If we consider the land cost, the value of c_{sp} will become much larger. The total site preparation cost can be expressed as:

$$C_{sp} = x \cdot C_{sp,0}\ (1 - b \cdot \log x) \quad (16)$$

Solar desalination systems require frequent maintenance and management to achieve good performance and this cost will increase with system age and decrease with system scale. A solar desalination system that produces x m^3/day freshwater production has a present discounted value of:

$$C_{f,n} = x \cdot (1 - b \cdot \log x) \cdot C_f \frac{(1+b_f)^{n-1}}{(1+\gamma)^n} \quad (17)$$

where n is the age of the plant, bf is the annual rate of increase in maintenance cost, and C_f (\$/(m^3/day)) is the normalized maintenance cost. To determine the present value of future cash flow, a discount rate γ (i.e. bank interest rate) is also considered.

Furthermore, seawater often undergoes a pretreatment process using filters, ion exchange resin, and chemicals prior to entering the desalination unit which consumes energy and incurs costs. Assuming that the price increase of the treatment chemicals is equal to the bank interest rate, then the present discounted value of the cost of the required treatment chemicals at the nth year can be written as:

$$C_{tc,n} = x \cdot (1 - b \cdot \log x) \cdot kDc_{tc} \quad (18)$$

where k is the ratio of the volume of inlet seawater to the volume of freshwater produced; c_{tc} (\$/m^3) is the specific cost of the treatment chemicals.

Table 1: Initial design parameters of solar MSF plant for economic evaluation

Design parameter	Value	Comment
P_r	7.5	Performance ratio of the desalination subsystem
D	365	Operating days of solar seawater desalination system per year
η_c	40%	Efficiency of solar collector
H	5 kWh/m^2/day	Average of daily global horizontal irradiance (GHI)
W_0	3.5 kWh/m^3	Required power consumption to produce 1 m^3 freshwater
h_{fg}	2.3 MJ/kg	Heat of vaporization of water
P_0	\$1.6/m^3	Unit freshwater price
β	6%	Annual freshwater and electricity price increase rate
γ	5%	Bank interest rate (discount rate)
α	5%	Other income as a percentage of freshwater income
C_{sc}	\$100/m^2	Construction cost of solar collector per unit area
c_2	\$20/kWh	Specific price of a 10-hour thermal energy storage
s	0.3	Ratio of stored energy to collected energy per day
η_s	15%	Photovoltaic solar cell power generation efficiency
c_{sp}	\$20/m^2	Average site preparation cost per unit area
Z	2	The ratio of entire area of the plant to the area of solar collectors and solar cells
C_e	\$225/m^2	Cost of solar cells per unit area
c_{tc}	\$0.06/m^3	The specific cost of the treatment chemicals
k	2	The ratio of the volume of inlet seawater to the volume of freshwater produced
$C_{1,0}$	A_0C_{sc}	Normalized solar collector construction cost
$C_{2,0}$	$A_0\eta_cHsc_2$	Normalized energy storage and pipeline subsystem construction costs
$C_{3,0}$	A_eC_e	Normalized solar photovoltaic cells construction cost
$C_{4,0}$	\$878/m^3	Normalized construction costs of the desalination system and related components
$C_{sp,0}$	$c_{sp} \cdot Z \cdot (A_0+A_e)$	Normalized site preparation cost
C_f	$D(0.025+0.095\frac{A_0+A_c}{A_0})$	Maintenance cost of the system per 1m3 freshwater production in the first year
ρ_w	1000 kg/m^3	Density of water
b	10%	Variation coefficient of the construction cost
b_0	10%	Other income variation coefficient with system scale
b_f	5%	Annual maintenance fee increase rate
P_e	\$0.20/kWh [48]	Unit electricity price

The total construction cost of the solar desalination system should be the sum of construction cost each subsystem detailed above, their related components, and operation and maintenance costs:

$$F = x \cdot (1 - b \cdot \log x) \cdot \left\{C + \sum_{n=1}^{N} C_f \frac{(1+b_f)^{n-1}}{(1+\gamma)^n} + NkDC_{tc}\right\} \quad (19)$$

where $C=C_{1,0}+C_{2,0}+C_{3,0}+C_{4,0}+C_{sp,0}$ is the initial normalized construction cost ignoring the scale factor. If the auxiliary equipment of solar desalination system is supplied by utility power rather than solar photovoltaic cells, the total investment cost can be written as

$$F = x \cdot (1 - b \cdot \log x) \cdot \left\{C + \sum_{n=1}^{N} C_f \frac{(1+b_f)^{n-1}}{(1+\gamma)^n} + NkDC_{tc}\right\} + x \cdot DW_0P_e \sum_{n=1}^{N} \frac{(1+\beta)^n}{(1+\gamma)^n} \quad (20)$$

Based on Eq. (19), the specific discounted water production costs (SDWPC) with unit \$/m^3 within the solar thermal desalination plant life time N can be calculated by Eq. (21):

$$SDWPC = \frac{(1-b \cdot log\, x) \cdot \left\{C + \sum_{n=1}^{N} C_f \frac{(1+b_f)^{n-1}}{(1+\gamma)^n} + NkDC_{tc}\right\}}{N \cdot D} \quad (21)$$

Benefit analysis of solar desalination system

There are two notable revenue streams in a desalination plant (Fig. 1): (1) produced freshwater, and (2) value-added products extracted from brine. The freshwater price is relevant to investment costs, system lifetime, bank interest and profit margin. Assuming that the local freshwater price is P_0 (\$/m^3), and the annual increase rate of freshwater price is comparable increase rate of electricity price (β), the price of water (\$/m^3) is:

$$P = P_0\,(1 + \beta)^n. \quad (22)$$

and the annual benefit from water production of a plant and present discounted value of water production benefit are:

$$Y_n = M_e \cdot P = \rho_w \cdot x \cdot D \cdot P_0\,(1 + \beta)^n \quad (23)$$

$$Y_{0,n} = \frac{Y_n}{(1+\gamma)^n} = \frac{\rho_w \cdot x \cdot D \cdot P_0 (1+\beta)^n}{(1+\gamma)^n} \quad (24)$$

In addition to the freshwater production, a solar desalination plant has the potential for additional income streams from valuable byproducts related to the brine or chemical products. The total income stream from a plant is:

$$Y_{1,n} = \alpha\,(1 + b_0 \cdot log x) \cdot Y_{0,n} \quad (25)$$

where α represents the ratio of income from valuable byproduct to that of freshwater. As the scale of the system increases, the proportion of byproduct income to freshwater income will increase, and the rate of this increase is denoted by b_0.

Assuming a system lifetime is N years, the total income of the system over the N-year period is

$$Y = \sum_{n=1}^{N} [Y_{0,n} + \alpha(1 + b_0 \cdot \log x) \cdot Y_{0,n}]$$
$$= \sum_{n=1}^{N} \frac{\rho_w \cdot x \cdot D \cdot P_0 (1+\beta)^n [1 + \alpha(1 + n_0 \cdot log\, x)]}{(1+\gamma)^n} \quad (26)$$

The ratio between the income generated to the overall cost for a solar desalination is represented by:+

$$\xi = \frac{Y}{F} = \frac{\sum_{n=1}^{N} \frac{\rho_w \cdot D \cdot P_0 (1+\beta)^n [1+\alpha(1+b_0 \cdot \log x)]}{(1+\gamma)^n}}{(1-b \cdot \log x) \cdot \left\{C + \sum_{n=1}^{N} C_f \frac{(1+b_f)^{n-1}}{(1+\gamma)^n} + NkDC_{tc}\right\}} \quad (27)$$

for a plant to be a viable investment, relative index ξ>1, and the payback period can be estimated when ξ =1.

Result and Discussion

The plant payback period can be extracted from the intercept between N and ξ=1. A solar desalination plant scaled to 1000 m^3/day has a payback period of 10 years, since its relative index (ξ) curve increases above 1 when the operating years (N) is larger than 10. The payback decreases with plant scale. The relative index (ξ) changes significantly when the rate of annual freshwater price increase rate (β) decreases to 0. At low increase rate, the relative index grows more slowly and the payback period increases more dramatically as the plant scale decreases. The payback period is 17 years for a plant producing to 1000m^3/day when the annual freshwater price increase rate is at 0.

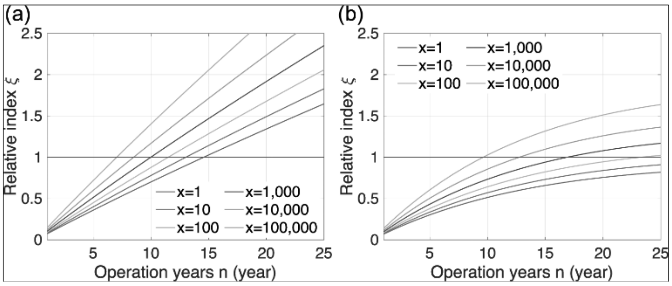

Fig 2: Relative index ξ changes with operation years when annual water price increase rate β is (a) 6% and (b) 0.

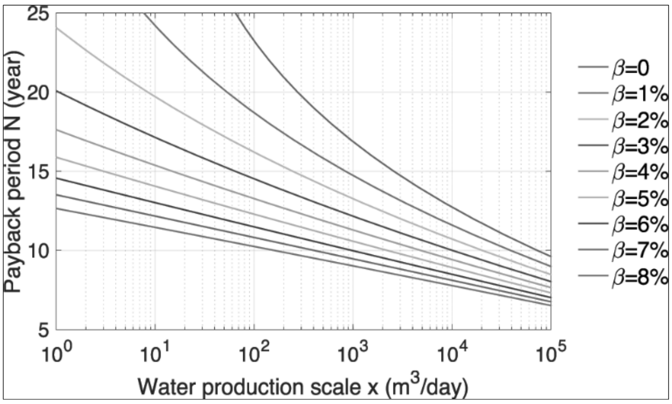

Fig 3: The payback period for solar multi-stage flash plant with varying water production scales, x (m3/day), and annual water price increase rate (β).

Fig. 3 can be more intuitive to represent Fig. 2. In the case of the same annual freshwater price increase rate, the larger the water production scale (x), the shorter the payback period. The smaller the annual freshwater price increase rate (β), the greater the negative impact on the system‘s economy. When β = 0 and 1%, the plant's water production scale should be greater than 66 and 8 m^3/day, respectively, to be able to get investment back within the system's 25-year lifetime.

Conclusion

The performance coefficient is inversely proportional to the payback period, whereas the unit price is directly proportional to the payback period. However, due to technical and manufacturing costs, the unit price of more efficient devices are usually higher. The solar collector construction cost takes the largest proportion (39%) of the total investment. The cost of solar collector per unit area (C_{sc}) and solar collector efficiency (η_c) of the alternative solar collectors should be carefully evaluated in order to achieve the shortest payback period. Since the investment in desalination subsystem accounts for only a small proportion (8%) of total investment, the normalized cost ($C_{4,0}$) and performance ratio (P_r) of desalination subsystem (especially when P_r>5) is less important than the solar collector price and performance.

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