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Technoeconomic analysis of solar thermal desalination

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ABSTRACT

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. Herein, we build a technoeconomic 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, local market and environmental factors of plant site on specific discounted water production costs and payback period. This approach eliminates technical and geographic constraints. The technoeconomic model attempts to predict the economics of a solar multi-stage flash distillation system. The specific discounted water production cost for a plant producing 1000 m^3/day is $\$0.97/m^3$ if the solar collector unit cost is $\$100/m^2$ and operates at 40% efficiency. According to market and environmental factors in seven coastal cities in the United States, the most economically feasible geographic location for a solar desalination plant is Miami, Florida.

1. Introduction

Geographic areas that are abundant with seawater or brackish water but lack freshwater resources require desalination technologies to meet water demands. Desalination is energy intensive, and thus there is a growing interest in coupling desalination with renewable energy sources (i.e. solar) [1, 2]. Two solar desalination approaches are as follows: (1) photovoltaic-reverse osmosis (PV-RO) and (2) solar-thermal desalination. The first approach generates electrical energy to drive a pressure-driven membrane separation process. The second approach uses heat collected by solar collector to drive a phase change separation process (e.g. multi-effect distillation (MED), multi-stage flash distillation (MSF), membrane distillation (MD), humidification-dehumidification (HDH)). There is a large technological space for designing and engineering solar desalination systems and technoeconomic analyses are necessary for future adoption [3-10].

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 [11]. Distillation systems can utilize the stored low grade heat in order to drive the desalination process [12, 13]. 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 [12, 14, 15]. Moreover, thermal desalination systems do not require stringent pretreatment [16] and have long operating lifetimes (20–30 years) [17, 18]. Prior pilot studies of solar-MED plants reveal that the construction cost of the evacuated tube solar collectors accounts for 53.9% of the total installed capital cost [19]. Thus, the economic viability of solar desalination systems is highly dependent on the solar collector. Detailed technoeconomic analyses are necessary to further understand the dependencies between system design, water price, and water production rate.

Typically, a contractor will consider the desalination technology, site selection, capacity, and plant lifetime in order to guide engineering and design. Running expenses and fixed expenses are important to consider when designing a solar desalination plant [20]. Running expenses primarily are associated with auxiliary costs incurred during operation. This may be chemicals for pretreatment or electricity costs for pumping. Thus, running expenses are highly dependent on the desalination and solar technology decision. In contrast, fixed expenses are fundamentally related to construction costs and depreciation considerations. Thus, fixed costs are often governed by geography, plant scale, and water economics (i.e. price of water). The water production cost of multi-stage flash and multi-effect distillation are similar ($\$1/m^3$) [21]. Research demonstrates that multi-effect distillation systems have higher construction costs and lower running expenses than multi-

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stage flash distillation. High constructions cost are associated with high material costs, and low running expenses are due to less auxiliary equipment and pretreatment chemicals [22].

Aside from running and fixed costs, the operating conditions of a solar desalination plant can also influence the long-term economic viability of a plant. Maintenance, market water price, fossil fuel and electricity pricing, geography, and plant scale all can influence performance and specific discounted water production (SDWPC). Regular maintenance ensures the performance of the solar desalination plant and is therefore not negligible. For instance, dust accumulation on the evacuated tube solar collectors can reduce water production of the solar desalination plant by 60% [23]. This occurs more readily on concentrated solar collectors than flat collector [24] and thus the selection and type of equipment chosen are likely going to influence operation and maintenance costs. Geopolitical factors can play a significant role in governing the economics of water pricing, government subsidies, and fossil fuel pricing. These factors are influential at the construction and operating stages. In terms of geographic location, distance from water sources (i.e. seawater), feedwater concentration, and solar irradiance can impact plant efficiency [25-27]. Thermal desalination technologies are generally not as sensitive to high concentrations solutions as the reverse osmosis in terms of energy consumption. However, low concentrations solution is less susceptible to scaling and thus requires less maintenance [27]. Thus, there is a plethora of different considerations that go into building and operating a solar desalination plant that go beyond simply the desalination technology type and geographic location.

Most technoeconomic studies on solar desalination either focus on a desalination technology or a specific geographic region [28-39]. However, in reality the performance of a desalination plant is dependent on a wide range of factors. This paper evaluates the technoeconomic of coupling solar collectors with thermal desalination systems. In section 2, the paper develops an analytical approach for discerning water production as a function of heat gain from a solar collector. Section 3 evaluates the technoeconomics of solar thermal desalination system via evaluation of fixed and operating cost. Section 4 is a benefit analysis which incorporates revenue streams of produced freshwater and value-added by-product. Section 5 evaluates the economics of a multi-stage flash desalination plant coupling with solar collectors. Section 6 summarizes the conclusion of the technoeconomic study. The analysis evaluates the unit cost, performance ratio, and scale of each component in a solar thermal desalination system (i.e. solar collector, heat storage, power supply, and desalination subsystem). Solar irradiance and market factors such as the local freshwater prices, bank interest, and electricity price are included in order to evaluate geographic-specific characteristics. The overall finding suggests that, to reduce the specific discounted water production costs (SDWPC) and payback period, designers should device with higher performance and lower unit cost and engineer system for longer service lifetimes and high production rates. In the specific analysis, when these goals are difficult to achieve at the same time, trade-off analysis should be carried out based on the proposed economic model.

2. Efficiency and water production of solar desalination system

The heat gains per day of a solar collector system at a given efficiency is calculated by "Hottel-Whillier-Bliss equation" [40, 41],

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

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 the annual water production M_e ($kg/year$) 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):

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

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.

3. 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 [42]. 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 $\gg 10\ m^3/day$). The construction cost for the solar collector system considering scale factor can be calculated as:

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

where $C_{1,0}$ ($\$/(m^3/day)$) is a normalized cost for a solar collector to produce 1 m^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:

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

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).

$$A_0 = \frac{\frac{\rho_w \cdot h_{fg}}{P_r} - W_0}{\eta_c H} \quad (7)$$

where W_0 ($\frac{kWh}{m^3/day}$) is the specific power consumption.

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

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

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

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

where $\eta_c H A_0$ 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.

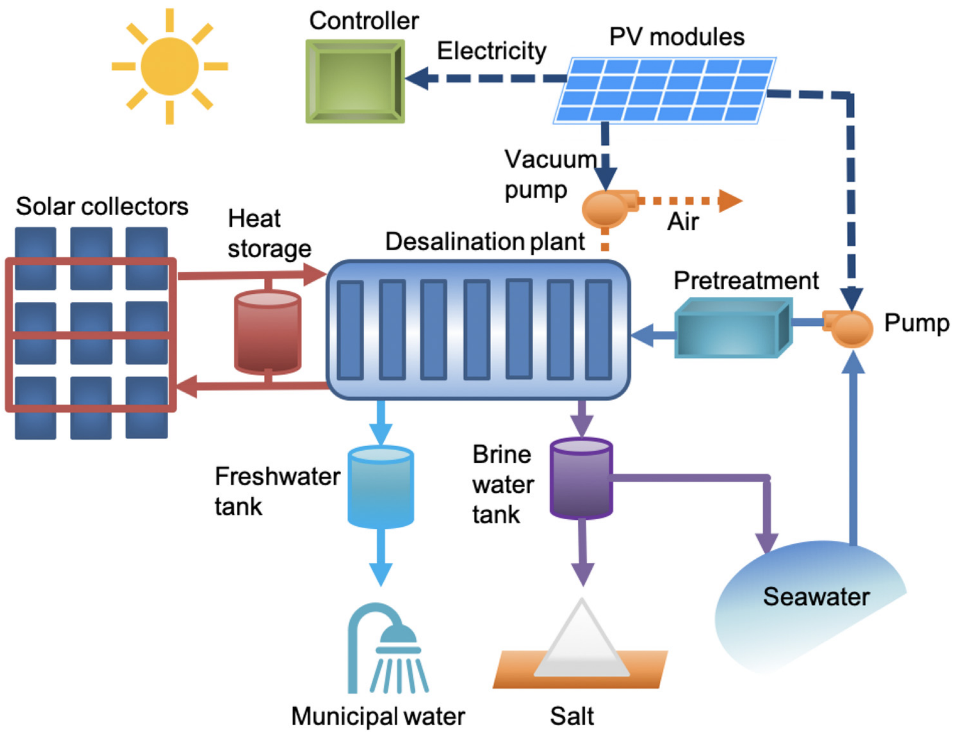

Fig. 1. Overview of solar thermal desalination plant which shows economic considerations.

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:

$$A_e = \frac{W_0}{\eta_s H} \tag{10}$$

The construction cost of power supply can be expressed by:

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

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

$$C_{3,0} = A_e\cdot C_e \tag{12}$$

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:

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

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:

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

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:

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

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:

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

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:

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

where n is the age of the plant, b_f 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 [43], 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:

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

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

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

Design parameter	Value	Comment
P_r	7.5 [20]	Performance ratio of the desalination subsystem
D	365	Operating days of solar seawater desalination system per year
η_c	40% [51]	Efficiency of solar collector
H	$5\ kWh/m^2/day$ [46]	Average of daily global horizontal irradiance (GHI)
W_0	$3.5\ kWh/m^3$ [47]	Required power consumption to produce 1 m^3 freshwater
h_{fg}	$2.3\ MJ/kg$	Heat of vaporization of water
P_0	$\$1.6/m^3$ [45]	Unit freshwater price
β	6% [45]	Annual freshwater and electricity price increase rate
γ	5% [52]	Bank interest rate (discount rate)
α	5%	Other income as a percentage of freshwater income
C_{sc}	$\$100/m^2$ [51]	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% [53]	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	$\$225/m^2$ [44]	Cost of solar cells per unit area
c_{tc}	$\$0.06/m^3$ [20]	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
$C_{4,0}$	$\$878/m^3$ [47]	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	$D(0.025+0.095\frac{A_0+A_e}{A_0})$ [20, 47]	Maintenance cost of the system per $1m^3$ 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

chemicals.

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:

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

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

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

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):

$$SDWPC = \frac{(1-b\cdot logx)\cdot\left\{C+\sum_{n=1}^{N}C_f\frac{(1+b_f)^{n-1}}{(1+\gamma)^n}+NkDc_{tc}\right\}}{N\cdot D} \tag{21}$$

4. 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 ($\$/m3$) is:

$$P = P_0(1+\beta)^n. \tag{22}$$

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

$$Y_n = M_e\cdot P = \rho_w\cdot x\cdot D\cdot P_0(1+\beta)^n \tag{23}$$

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

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

$$Y_{1,n} = \alpha(1+b_0\cdot logx)\cdot Y_{0,n} \tag{25}$$

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

$$\begin{aligned} Y &= \sum_{n=1}^{N}[Y_{0,n}+\alpha(1+b_0\cdot logx)\cdot Y_{0,n}] \\ &= \sum_{n=1}^{N}\frac{\rho_w\cdot x\cdot D\cdot P_0(1+\beta)^n[(1+\alpha(1+b_0\cdot logx)]}{(1+\gamma)^n} \end{aligned} \tag{26}$$

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

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

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

5. Economic evaluation for a solar desalination system

The economic analysis described above can provide assessment for a simple solar thermal desalination model. Table 1 presents some typical value of design parameters of a solar multi-stage flash (MSF) desalination system in Oakland, California. The auxiliary components of the system are powered by photovoltaic modules.

The calculation note for Table 1 are shown below.

A. Cost of solar collectors per unit area is estimated by the summation of specific cost of collector and specific cost of heat transfer fluid (HTF) receiver.
B. The typical cost of photovoltaic modules in Europe is $\$1.5/W$. When $\eta_s = 15\%$, and solar radiation intensity is 1000 W/m^2, C_e is approximately equal to $\$225/m^2$ [44].
C. The average annual price escalation rate of water utility in East Bay Municipal Utility District in California is 6.06%, according to the historical data from 2008 to 2016. So β is estimated into 6%. And in 2016, the volume charge is $\$5.94/kGal$, which approximately equates to $\$1.6/m^3$ [45].
D. The daily GHI in Oakland, California is between 4.8 and 5.3 $kWh/m^2/day$. Then the H can be estimated to 5 $kWh/m^2/day$ [46].
E. Typical specific energy consumption (including electric energy) for MSF Plants is 304 MJ/m^3. Therefore, P_r can be approximately calculated to be 7.5 [20].
F. If the salinity of the feed seawater is 0.35%, the salinity of the discharged concentrated brine is 0.7%, and the density of seawater is approximately considered equal to the density of freshwater, k will be calculated as 0.5.
G. The specific maintenance cost of desalination subsystem is taken as $\$0.025/m^3$ [20], and the specific maintenance cost of solar collector array is $\$0.095/m^3$[47]. When the system is equipped with solar cells, assume the maintenance cost of solar cell is equal to that of solar collector per unit area.
H. The electricity price in California is ¢$19.90/kWh$ in June 2018 [48]. It can be estimated into $\$0.20/kWh$.

To further analyze the impact of specific parameters on the system economic, according to the function given above, the curve of the studied parameters taking different values will be drawn, while the other parameters remain unchanged.

5.1. Effects of plant scale, system lifetime and investment cost on SDWPC

The specific discounted water production costs (SDWPC) for the analysis of the solar multi-stage flash desalination model decreases linearly to the logarithmic of the plant scale (Fig. 2). The SDWPC

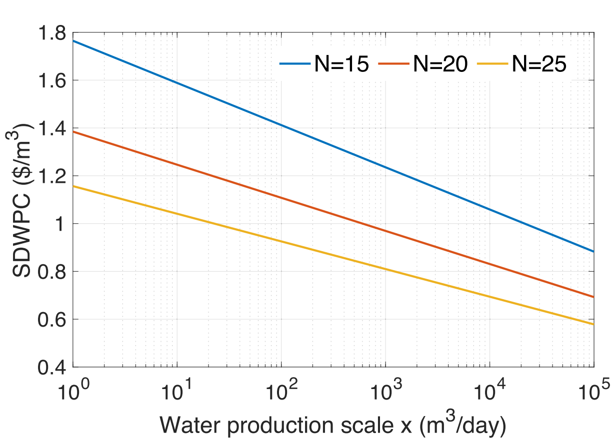

Fig. 2. The impact of system lifetime N (year) and scale x (m^3/day) on specific discounted water production costs (SDWPC).

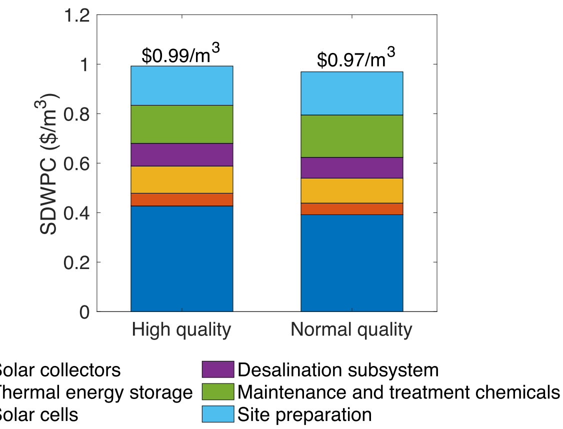

Fig. 3. Breakdown specific discounted water production costs (SDWPC) of plant with high-quality and normal-quality equipment.

decreases linearly with $logx$ because the model assumes that the unit construction cost and maintenance cost linearly decrease with $logx$. A typical plant can last between 15 and 25 years. Plants that have longer lifetimes (i.e. 25 years) demonstrate significantly lower specific discounted water production costs than plants with accelerated lifetimes of 15 years. For instance, for a plant scale of ~1000 m^3/day, SDWPC dropped from $\$1.24/m^3$ to $\$0.81/m^3$ when the system life increased from 15 years to 25 years. The reduction is due to the fact that systems with longer life have capability to produce more water.

The specific discounted water production costs can help guide a plant manager on the selection of equipment. In general, using higher quality equipment can enhance system lifetime and reduce unit maintenance costs, but unit construction costs can increase. For a target plant with scale of 1000 m^3/day deciding between a higher grade equipment that is 20% more expensive is expected to increase the system lifetime from 20 years to 22 years, and reduce the maintenance cost by 20% per year. Given these assumptions, the SDWPC is $\$0.02/m^3$ higher due to higher initial construction cost (Fig. 3).

5.2. Effect of annual freshwater price increase rate on payback period

The ratio between the fiscal output of a solar desalination plant (i.e. water, chemicals) and input costs (i.e. construction, maintenance) increases with both operating years (N) and plant scale (x) (Fig. 4a). The plant payback period can be extracted from the intercept between N and $\xi = 1$. 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 1000 m^3/day when the annual freshwater price increase rate is at 0.

Fig. 5 can be more intuitive to represent Fig. 4. 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 $\beta = 0$ 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.

5.3. Trade-offs between electricity sources for auxiliary equipment

While thermal energy is the dominant energy source for the desalination subsystem in the model, electrical energy is necessary to power auxiliary equipment in a plant (i.e. pumps, vacuums). Electricity for

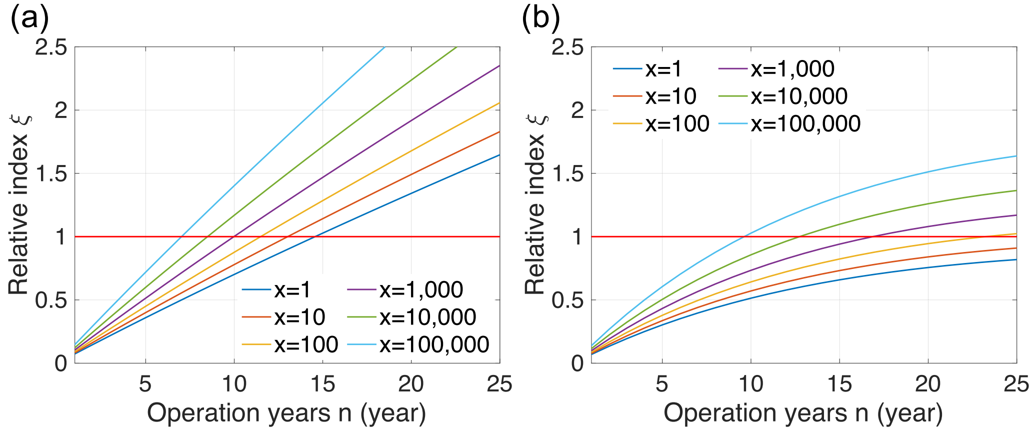

Fig. 4. Relative index ξ changes with operation years when annual water price increase rate β is (a) 6% and (b) 0.

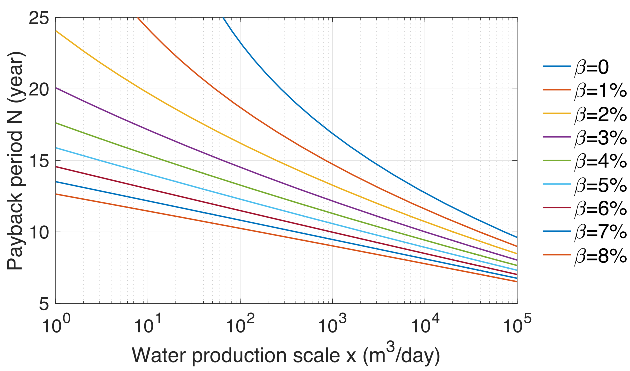

Fig. 5. The payback period for solar multi-stage flash plant with varying water production scales, x (m^3/day), and annual water price increase rate (β).

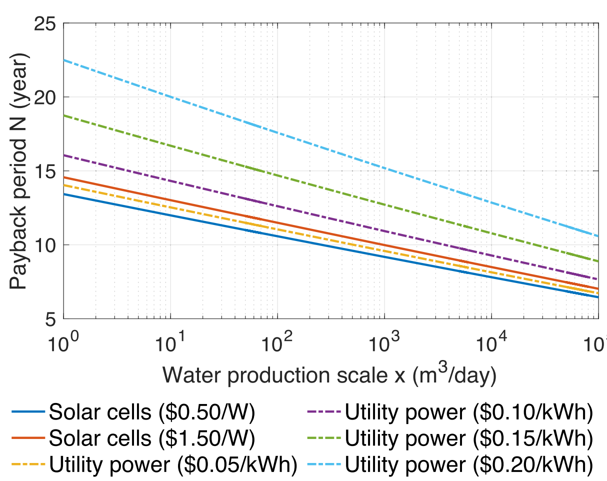

Fig. 6. Economic comparison when the auxiliary devices of the system are powered by solar cells with cost of *\$0.5/W* and *\$1.5/W*, and utility power with electricity price P_e of *\$0.05/kWh*, *\$0.10/kWh*, *\$0.15/kWh*, and *\$0.20/kWh* respectively.

auxiliary equipment can come from the power grid or from solar photovoltaic sources. The former, can only occur in geographic locations equipped with a centralized energy generation system and is less practical for developing worlds. In contrast, photovoltaic cells can provide distributed energy sources, but require ample solar irradicance to effective yields. The cost of each power source is dependent on a variety of factors including and not limited to the cost of electricity, construction cost, maintenance costs, and geography (Eq. (19) and Eq. (20)). If we assume an electricity price (P_e) of approximately *\$0.20/kWh*, it is more advantageous to use solar photovoltaic power sources, rather than electric grid power, for solar MSF desalination plants producing less than 100,000 m^3/day (Fig. 6). Electricity price in region with abundant fossil fuel resources may be reduced. When the price drops below the critical value of *\$0.067/kWh*, and other parameters remains the same, it is more economical to use the power grid compared with solar photovoltaic cells with cost of *\$1.50/W*. As the cost of solar cells drop to *\$0.50/W*, it would be more competitive than the utility power with unit cost larger than *\$0.032/kWh*.

5.4. The impact of solar collector cost and efficiency on plant economics

The largest investment in a solar-multi-stage flash (MSF) desalination plant are the solar collectors. This cost is nearly 39% for a plant with a 20-year lifetime (Fig. 3). Efficient and affordable solar collectors are thus advantageous for decreasing the payback period of a plant. The payback period decreases linearly and proportionally to the the cost of solar collector (C_{sc}) (Fig. 7a). The unit cost of solar collector is limited by geographic, manufacturing and technical factors. For a solar desalination plant built in a remote area, such as a small island, due to the transportation costs, the unit cost of the solar collector will be more expensive. High-quality solar collectors are expensive but may require less maintenance and have a longer service life. More efficient solar collectors might also cost more due to higher technical and manufacturing level. For example, one-axis tracking solar collectors can achieve higher daily efficiency than stationary solar collector, but require high cost to install and operate them [40, 49, 50]. In general, unit cost and efficiency (η_c) of solar collector are correlated. Higher efficiency of solar collector can reduce payback period. However, as the solar collector efficiency increases, the effect of increasing the efficiency on shortening the payback period is less obvious (Fig. 7b).

The surface map can help plant designer make trade-offs between unit cost and efficiency of solar collectors. For instance, there are two options of solar collectors available, the first plan has a unit price of $\$163/m^2$, and the efficiency is 61%; the second plan has a cheaper unit price of $\$129/m^2$, but the efficiency is relatively lower, 54%. When system scale x is fixed to 1000 m^3/day, the former payback period is about 9.5 years, which is higher than the latter's 9.2 years (Fig. 8). Hence, the second type of solar collector is preferable.

5.5. The impact of performance ratio and normalized construction cost of desalination subsystem on plant economics

The desalination subsystem is an important part of the solar desalination plant. Hence, its economy are also worth exploring. As performance ratio (P_r) increases, the length of payback period is decreasing

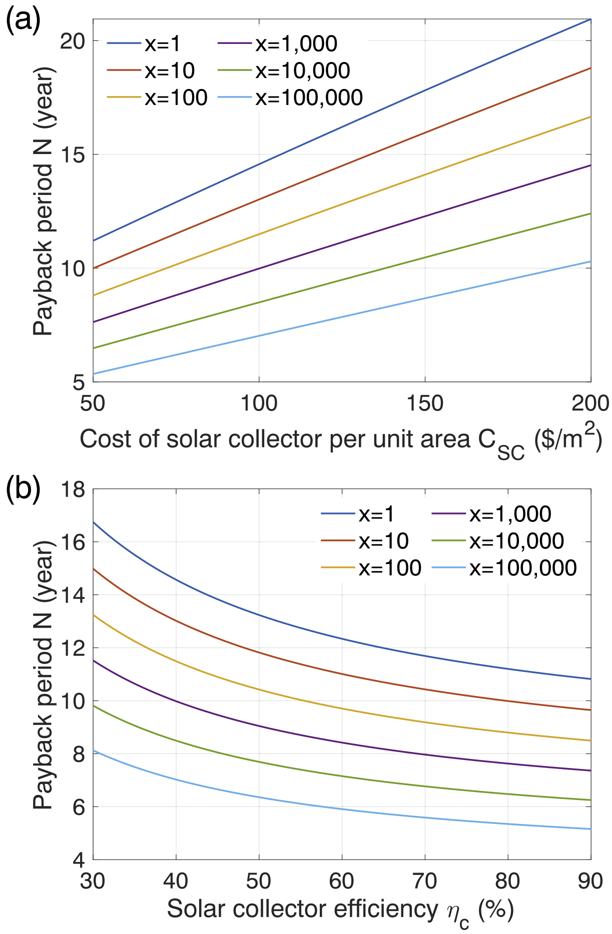

Fig. 7. The payback period for solar-MSF plants with varying water production scales (m^3/day) and with varying the area normalized solar collector costs (a). The payback period for solar multi-stage flash plants with respect to solar collector efficiency (η_c) (b).

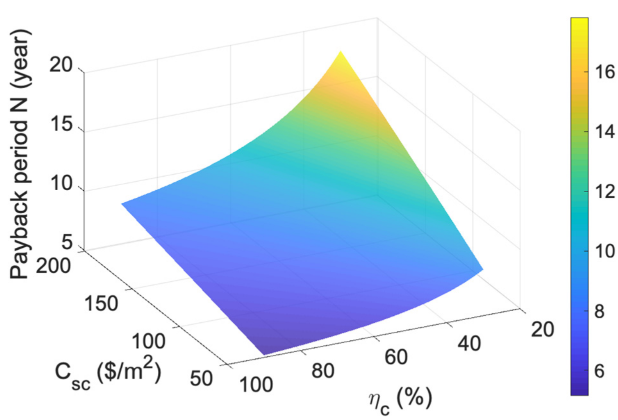

Fig. 8. The impact of both cost per unit area C_{sc} and efficiency η_c of solar collector on payback period when the system scale $x = 1000$ m^3/day.

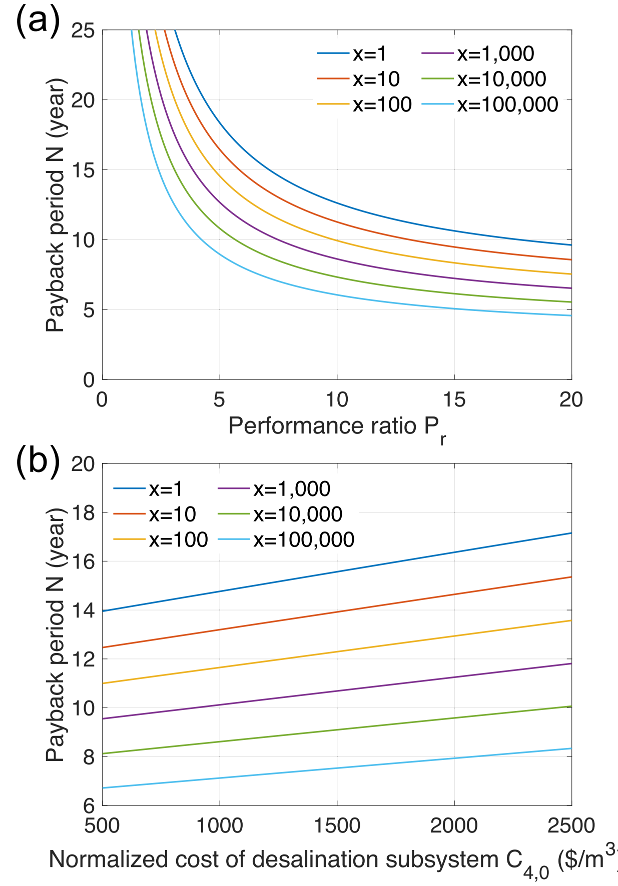

Fig. 9. The impact of (a) performance ratio P_r and (b) normalized cost of desalination subsystem $C_{4,0}$ on payback period at different system scale x m^3/day.

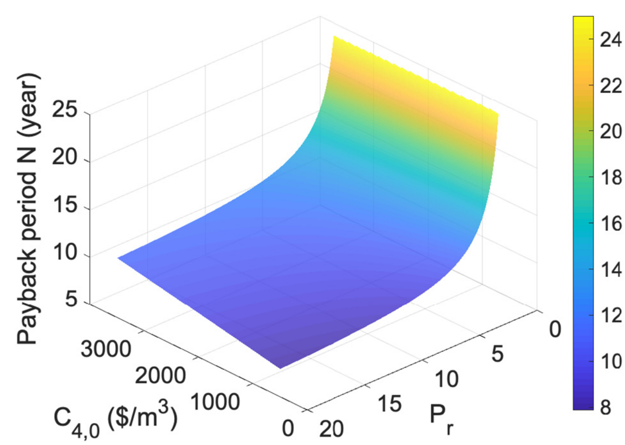

Fig. 10. The impact of both (a) performance ratio P_r and (b) normalized cost of desalination subsystem $C_{4,0}$ on payback period when the system scale $x = 1000$ m^3/day.

(Fig. 9a). However, the decrease rate become slower and slower. That is, when the performance ratio is small, the effect of improving performance ratio on the economy of the system is more significant. When system scale is 1 and 1000 m^3/day, the performance ratio should be at least greater than 3.1 and 1.9, respectively, so that the system can be profitable over a 25-year lifetime. The normalized construction cost of desalination subsystem ($C_{4,0}$) is positively proportional to the payback period (Fig. 9b). However, since the construction expenditure of the desalination subsystem accounts for a relatively small proportion (8%) of the total expenditure of the system (Fig. 3), the impact of the change of desalination subsystem normalized construction cost on the payback period is not as significant as unit cost of solar collector. When the performance ratio (P_r) is relatively small (e.g. less than 5), it has a more significant impact on the payback period compared with normalized cost of desalination subsystem ($C_{4,0}$) when system scale (x) is 1000 m^3/day (Fig. 10). At this time, it is more preferable to consider a system with a larger performance ratio. Larger performance ratio represents that the thermal desalination system has a higher water production

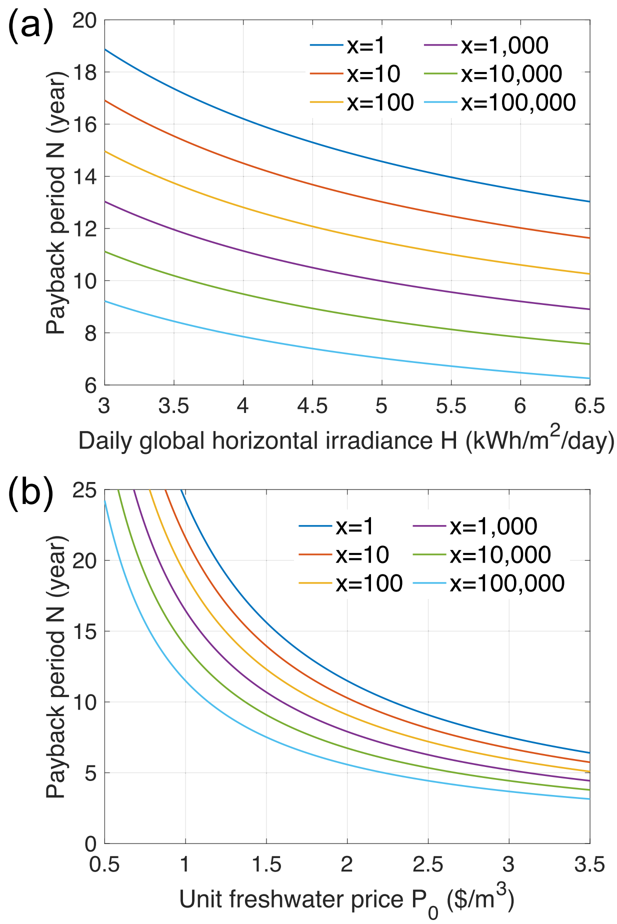

Fig. 11. The impact of (a) daily global horizontal irradiance (GHI) H and (b) unit freshwater price P_0 at different system scale x (m^3/day).

yield for a given collected energy. However, the system with higher performance ratio usually means that it has more stages or effects, and its requirements for technology and manufacture will also increase, which increase the total construction cost at the same time. Therefore, desalination subsystem performance ratio and normalized construction cost are closely related. It is important to analyze the economy of the system with the combination of these two parameters, especially when performance ratio is relatively large.

5.6. Siting of solar desalination plant

The siting of the solar desalination plant is a factor that must be considered. Apparently, constructing a plant in a region where there is plenty of sunshine and water scarcity can make the system more economical and profitable. Daily average solar irradiance (H) can evaluate the solar energy abundance of a region. As solar irradiance becomes larger, the length of payback period will become shorter (Fig. 11a). Local water price (P_0) can help assess the extent of local water shortages. In regions where freshwater supply is difficult to meet the demand, local water prices will be relatively higher. In order to make the designed solar thermal desalination plant profitable and competitive in the local market, the freshwater produced should be priced at or below local utility water price on a premise that it could be profitable within the plant lifetime. The smaller the water price, the worse the system economy is (Fig. 11b). And the rate of this change, which is nonlinear, increases with the decrease of water price. The proposed multi-stage flash solar desalination plant would not be profitable within 25 years if its freshwater price is set below than 0.5 $\$/m^3$ when $x \leq$ 10,000 m^3/day. Therefore, it is essential to fully examine the local water price history, water availability and demand in the target area for site selection.

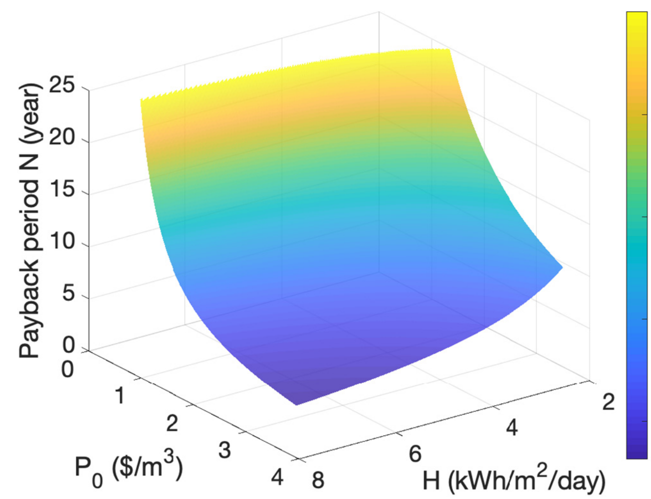

Fig. 12. The impact of both daily global horizontal irradiance (GHI) H and unit freshwater price P_0 on payback period when system scale $x = 1000$ m^3/day.

Curved surface maps of daily average global horizontal irradiance (H) and unit water price (P_0) can help a designed system with 1000 m^3/day water production scale to choose a suitable location or a reasonable water price that can shorten the payback period (Fig. 12).

Based on the above analysis, the following example can help illustrate the siting selection method of the solar desalination plant. The daily average global horizontal irradiance (GHI) per day (H), utility water price (P_0) for local large commercial customers, and the annual utility water price increase rate (β) of seven different coastal cities of the United States are given (Table 2). Assume other than these data, the rest of parameters remain unchanged. Then according to the calculation results based on economic model, when $x \leq$ 100,000 m^3/day, it is most economical to build a plant in Miami, since its unit water price, annual water price increase rate and daily GHI are all relatively high (Fig. 13). The second and third places are respectively Oakland and Seattle. Although Seattle‘s water price and its increase rate are both higher than that of Oakland, its daily GHI is 1.6 $kWh/m^2/day$ lower than Oakland, affecting the economy of the system in Seattle. The solar desalination plants in Jacksonville, Newport News and Conway are less economical, and their water production scale must be large enough to get the investment back within the expectation of service lifetime. Due to the low local water price in Savannah, the proposed plant would be completely uncompetitive in the market and cannot be payoff within the system lifetime. So it is not recommended.

However, the above is only a rough comparison between the cities. In actual and specific planning, we cannot ignore many other factors that can affect the siting selection, such as local government subsidies, transportation fee of facilities, local land prices. If the desalination plant is built in the outskirts of the city in order to save land prices, we should also consider the influence of additional piping cost on system economics.

6. Conclusion

Solar thermal desalination technologies may be an viable approach toward addressing growing water shortages across the globe. However, the economics of solar desalination depends on a variety of factors including and not limited to the cost of water, the cost of grid electricity, and the efficiency of each component (solar collector, desalination subsystem, etc.). In order to design economic solar desalination plant, there is a need for technoeconomic analyses. This paper presents an economic model capable of evaluating the economics of multi-stage

Table 2
P_0, β and daily GHI in different coastal cities of the United States [45, 46].

State	City	Water utility	β (%)	P_0 ($\$/m^3$)	Average of daily GHI ($kWh/m^2/day$)
CA	Oakland	East Bay Municipal Utility District	6.06	1.57	5.0
WA	Seattle	Seattle Public Utilities	7.26	1.82	3.4
FL	Miami	Miami Dade Water and Sewer Department	6.58	1.97	5.3
FL	Jacksonville	JEA	7.06	0.49	5.1
GA	Savannah	City of Savannah	3.12	0.41	4.9
VA	Newport News	Newport News Waterworks	1.35	1.29	4.5
SC	Conway	Grand Strand Water and Sewer Authority	0.09	1.3	4.7

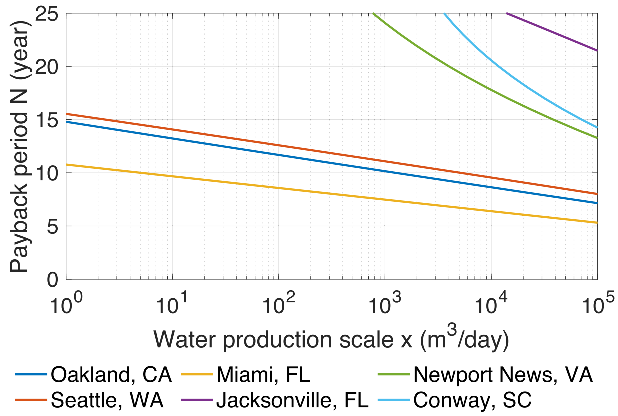

Fig. 13. Economic comparison of the solar multi-stage flash desalination plant with different system scale x (m^3/day) in different coastal cities in the United States.

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 an equal percentage maintenance costs and extend service life for 2 years.

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.

Solar thermal desalination plants are suitable for areas with abundant solar energy and severe water scarcity. Using solar irradiance (H) and unit freshwater price (P_0) to evaluate solar and water resources, the economic model can help guide plant location. According to solar irradiance, water price and the increase rate, this model analyzes the economic feasibility of the solar MSF plant in seven coastal cities in the United States. The results show Miami and Oakland are preferable locations for a solar desalination plant. The least economical city is Savannah, due to the low local freshwater price.

Declaration of competing interest

The authors have no conflict of interest with the work presented within the Journal Article.

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