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Life cycle cost analysis of a sustainable solar water distillation technique

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ABSTRACT

This paper presents a detailed estimation of the fabrication cost, water production cost (WC), and cost payback period (CPP) using annualized life cycle costing for a tubular solar still (TSS). The operation and maintenance cost (OM) and the number of sunny days in a year (d) have a significant effect on the WC. The WC is raised from 3.1 to 4.4¥/L, if the OM increases from 5 to 18% of the capital cost, respectively. The WC is dropped by 35% (in average) when the *d* increases from 230 to 350 days. In addition, the CPP is greatly affected by the water selling prices and *d*. The CPP is dropped from 68 to 45 days due to the increase of *d* from 230 to 350 days (in average), respectively. The fabrication cost of the TSS ($5) and the WC ($31/m^3) are affordable and much lower than the single-sloped passive solar still. Finally, it is revealed that the solar radiation is the most influential parameter on the productivity of TSS and a linear proportional relationship is found between them.

Keywords: Tubular solar still (TSS); Water cost; Life cycle cost; Payback period; Production; Solar radiation

1. Introduction

Although water covers about two-thirds of the earth's surface, most of it is too salty for use and only 2.5% is fresh water. As a result, many people suffer due to the shortage of safe drinking water in arid, remote, and coastal areas in Bangladesh, India, Kenya, Ethiopia, Peru, Nigeria, and the countries of the Arabian Gulf [1]. Figs. 1 and 2 show the scenarios of water scarcity in India and Nigeria, respectively [2,3]. In 1999, the UNEP reported that 200 scientists in 50 countries identified water shortage as one of the two most worrying problems for the new millennium [4]. According to the UNESCO (2006), about 1.1 billion people cannot have easy access to safe drinking water [5,6]. The World Bank and the United Nations warned

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Fig. 1. Women and children wait for water supply in India (2008, AP Photo) [2].

Fig. 2. Thirsty people try to get water from a nearly dried-up well in Nigeria (2007) [3].

that the world needs to act urgently to avoid a global water crisis [7–9]. The rise of seawater level associated with the global warming has caused the seawater intrusion toward inlands in many parts of the world, e.g. Australia, Grand Cayman, Bahamas, Barbados, Bangladesh, Belize, Jamaica, the USA, and Vietnam [10–14]. According to the IPCC, the sea level rise will not only extend the areas of salinity, but will also decrease the freshwater availability in coastal areas [10].

Many researchers have investigated solar stills of different designs, e.g. simple solar still [15,16], single-slope single-basin solar still [17], tubular-type [18–22], and hemispherical solar still [23,24]. The performance of a solar still has been improved using a hybrid photovoltaic/thermal system [25], an evacuated tubular collector integrated still [26], a concentrator with a phase change material [27], and a sun-tracking photovoltaic system [28]. Besides, a solar still was also used to refine and treat wastewater [29]. A complicated system is, however, generally costly and may require regular monitoring with skilled personnel, which makes the complicated system unsuitable for use in remote and coastal areas [30]. Therefore, a tubular solar still (TSS) has been designed and tested to produce potable water from seawater using renewable (solar) energy for a small society in remote, arid, and coastal areas (Fig. 3). It can be installed near a house for the purpose of reducing time and labor (of residents) involved in carrying of potable water from far places. Moreover, the TSS is made of cheap, durable, lightweight, and locally acquisitioned materials to reduce the installment and maintenance cost.

The economics of the energy system is essential to understand the cost of production and payback periods on the investment to reduce the risk of project failure. The life cycle cost analysis of the solar still depends on several key variables such as initial investment, bank benefit rate, annual distillate yield, operational and maintenance cost, life time of solar stills, production cost of distilled water, selling price of distilled water, number of sunny days in a year, and salvage value of the materials [31].

Tleimat and Howe [32] found that a solar distillation plant of daily capacity less than 200 L is more economical than high capacity plants. Sinha et al. [33] carried out a techno-economic analysis on an active solar still with a water heater considering the design life of 14 years. Mukherjee and Tiwari [34] carried out the economic analysis on three different types of stills and concluded that the minimum water cost comes from conventional types. It was estimated that about 25% of the water cost attributes to the energy cost

Fig. 3. Pictorial view of solar still.

(e.g. fossil fuel) [35]. In remote areas, the acceptable water cost was \$0.03/L (i.e. ¥3/L) for potable uses, if water was produced from solar stills [36]. The operational and maintenance cost of solar stills is less and required only for clearing the troughs, inserting the raw water, and collecting the yield. Therefore, the cost may mainly depend on the initial investment.

In this paper, a detailed estimation of the fabrication cost, water production cost (WC), and payback periods using the annualized life cycle costing (LCC) for the TSS are described. The effects of the maintenance cost and the number of sunny days on the WC were obtained. In addition, the variations of payback periods with different water selling prices and a number of sunny days were observed. Finally, a linear proportional relationship was proposed between the solar radiation and the productivity of TSS. The economics of the TSS using the annualized LCC has not been presented by any researchers before.

2. Application of TSS

Massive scale arsenic (As) contamination in groundwater is another major concern in many countries, e.g. Argentina, Mexico, Chile, USA, Taiwan, Mongolia, Thailand, The Philippines, China, Japan, New Zealand, Vietnam, Cambodia, India, Bangladesh, and Nepal [37–39]. Drinking of As-contaminated water is linked with skin problems, such as cancer, cardiovascular diseases, neurological diseases, eye problems, and other diseases [40,41]. The TSS could be able to remove not only salt from water but also As, iron, and pathogens. In addition, a lightweight compact still (e.g. TSS) would be reasonable and practical when a water supply system is cut-off due to natural disasters (e.g. tsunami). The key advantages of the TSS include on-site easy assembling, easy operation and maintenance, thermal insulation materials are not required, highly durable (5 years), lightweight (0.6 kg/TSS), portable size (1×0.13 m), and satisfactory pure water production rate ($5\,\mathrm{L/m^2\,d}$).

3. Life cycle costing

The annual uniform cost (AC) of the TSS is estimated using the annualized LCC [42] as follows:

$$\mathrm{AC} = (\mathrm{Cp} + \mathrm{OM}) \times C_{\mathrm{RF}} - S_L \times C_{\mathrm{SF}} \quad (1)$$

where

$$\mathrm{Cp} = (\text{Cost of a TSS} + \text{labor cost}) \times N \quad (2)$$

$$C_{\mathrm{RF}} = r(1+r)^n/[(1+r)^n - 1] \quad (3)$$

$$C_{\mathrm{SF}} = r/[(1+r)^n - 1] \quad (4)$$

The annual operational and maintenance cost (OM) of the TSS includes the cost for inserting saline water, collecting distilled water, cleaning the trough, repairing the cover, and monitoring the system. The salvage (scrap) value of different components (S_L) of the TSS is less in developed countries and is higher in developing countries. Presently, different agencies and banks (government and private) offer different benefit rates (r) for borrowers to encourage renewable energy programs. The number of sunny days in a year (d) varies from country to country. Usually, d is higher in arid regions (e.g. Middle East) than any tropical countries. In this *LCC* analysis, OM = 5, 7, 10, 12, 15, and 18% of *Cp*; $S_L = 5\%$ of *Cp*; $r = 4$, 8, and 12%; $d = 230$, 250, 280, 300, 330, and 350 days; $Ps = 30$, 50, 70, 90, 110, and 130 ¥//L; $n = 5$ years; and $N = 50$ are considered. Therefore, the distilled WC per liter (WC) is expressed as:

$$\mathrm{WC} = \mathrm{AC}/W \quad (5)$$

Finally, the cost payback period (CPP) is defined [31] as

$$\mathrm{CPP} = \ln[CF/(CF - Ps \times r)]/\ln(1+r) \quad (6)$$

where $CF = W \times Ps$. Note that $CF = AC$, if the distilled water is sold at the production cost (i.e. WC) and the CPP mainly depends on the *CF*.

4. Field experiments on TSS

A number of field experiments were carried out in Fukui, Japan (University of Fukui) and in Muscat, Oman (Sultan Qaboos University) to evaluate the daily production performance of the TSS. In 2008, two identical TSSs were setup and investigated from June to December in Japan and Oman, respectively. The experimental equipment consisted of two TSSs, a pyranometer, a data logger, two thermo-hygrometers, 25 thermocouples, and two electric balances connected to two laptops. Table 1 shows the list of instruments with errors.

5. Results and discussion

5.1. Fabrication cost of a TSS

Table 2 shows the estimated fabrication cost of a TSS. The total cost is ¥497 (≈\$5) and ¥1,297 (≈\$13)

Table 1
List of instruments with errors

Instruments	Company	Function	Range	Error
Data logger	MCS	To record all measured data (temperature and relative humidity)	0–100℃, 0–100% RH	±2%
Electric balance	METTLER TOLEDO	To measure the weight of produced water	0–3 kg	±0.01 g
Pyranometer	EKO	To measure the intensity of solar radiation	0–20 mV	±1%
Thermo-hygrometer	VIASALA	To measure the relative humidity inside the still	0–100%	±2%

Table 2
Estimated fabrication cost of a TSS

Items	Amount	Unit cost	Cost (¥)
Polythene film (0.15 mm thickness)	0.68m^2	¥185/ m^2	126
Carton paper	–	0	0
Black polythene film for trough	1 p.	¥98/10 p.	18
Metallic pipe for frame (6 mm diameter)	2 p.	¥105/2 p.	105
Metallic wire for frame (1.2 mm diameter)	8 m	¥300/50 m	48
G17 glue	50 ml	¥488/170 ml	144
Scotch tape	10 m	¥128/50 m	26
Miscellaneous	–	–	30
Fabrication cost			497
Labor cost (unskilled person)	4 h	¥200/h	800
Total cost (including labor cost)			1,297*

Notes: p: piece. ¥: Japanese yen. US$1 ≈ ¥100. *The average life of the TSS is considered as five years. Therefore, the additional cost to fabricate four more troughs (because the life of trough is about a year, however, the life of a cover and a frame is about five years) must be included in the unit cost [1,297 + 4(18 + 144 + 200) = ¥2,745].

without and with considering the labor cost, respectively. In Japan, the prices of the fabrication materials were expensive and the labor cost was high. It is, therefore, predicted that the fabrication cost will be dropped by at least one-third in developing countries, e.g. India, Nigeria, and Bangladesh, where fabrication materials are less expensive and the labor cost is obviously low. Moreover, the fabrication cost would be reduced when fabricating a large number of TSSs commercially.

5.2. Water production cost

A number of key factors affect the WC and payback periods of a solar still. Nevertheless, two notable factors among them are durability and productivity. Table 3 shows the estimated WC [by Eq. (5)] and the CPP [by Eq. (6)] for a plant which consists of 50 TSSs. The WC is raised from 3.1 to 4.4¥/L due to the increase of OM from 5 to 18% of *Cp*, respectively. Besides, *r* slightly affects the WC.

Fig. 4 shows the variations of the WC with the different OMs. If the OM is increased from 5 to 18% of *Cp*, the WC increases by 12.4% (in average). It indicates that the *r* and OM greatly affect the WC. Fig. 5 presents the variations of the WC with the different *d*. The WC is dropped by 35% (in average) when the *d* increases from 230 to 350 days. Additionally, the effect of *r* on the WC is very significant. Therefore, it is revealed from the figures (Figs. 4 and 5) that the *r*, OM, and *d* highly affect the WC.

Many researchers studied the *LCC* analysis of the passive solar still under different climatic conditions. The results were, therefore, quoted for the purpose of comparison. Table 4 shows the cost of distilled water for various designs of solar still. The WC is about \$31/m^3 for the TSS, which is much lower than the single-sloped passive solar still, but very close to the pyramid-shaped solar still. In general, it could be concluded that the solar stills can be implemented to produce distilled water at a reasonable cost.

Table 3
Estimated WC and CPPs

Cp (¥)	${}^{\Delta}S_L$ (¥)	OM* (¥)	*r*	C_{RF}	C_{SF}	AC (¥)	W^a (L/yr)	WC (¥/L)	*Ps* (¥/L)	*CF* (¥)	CPP (yr)
137,250	6862.5	6862.5	0.04	0.225	0.185	31,105	10,050	3.1	30	301,500	0.47
137,250	6862.5	6862.5	0.08	0.250	0.170	34,924	10,050	3.5	30	301,500	0.48
137,250	6862.5	6862.5	0.12	0.277	0.157	38,898	10,050	3.9	30	301,500	0.50
137,250	6862.5	9607.5	0.04	0.225	0.185	31,721	10,050	3.2	50	502,500	0.28
137,250	6862.5	9607.5	0.08	0.250	0.170	35,612	10,050	3.5	50	502,500	0.29
137,250	6862.5	9607.5	0.12	0.277	0.157	39,659	10,050	3.9	50	502,500	0.29
137,250	6862.5	13725.0	0.04	0.225	0.185	32,646	10,050	3.2	70	703,500	0.20
137,250	6862.5	13725.0	0.08	0.250	0.170	36,643	10,050	3.6	70	703,500	0.20
137,250	6862.5	13725.0	0.12	0.277	0.157	40,802	10,050	4.1	70	703,500	0.21
137,250	6862.5	16470.0	0.04	0.225	0.185	33,263	10,050	3.3	90	904,500	0.16
137,250	6862.5	16470.0	0.08	0.250	0.170	37,330	10,050	3.7	90	904,500	0.16
137,250	6862.5	16470.0	0.12	0.277	0.157	41,563	10,050	4.1	90	904,500	0.16
137,250	6862.5	20587.5	0.04	0.225	0.185	34,188	10,050	3.4	110	1,105,500	0.13
137,250	6862.5	20587.5	0.08	0.250	0.170	38,362	10,050	3.8	110	1,105,500	0.13
137,250	6862.5	20587.5	0.12	0.277	0.157	42,705	10,050	4.2	110	1,105,500	0.13
137,250	6862.5	24705.0	0.04	0.225	0.185	35,112	10,050	3.5	130	1,306,500	0.11
137,250	6862.5	24705.0	0.08	0.250	0.170	39,393	10,050	3.9	130	1,306,500	0.11
137,250	6862.5	24705.0	0.12	0.277	0.157	43,848	10,050	4.4	130	1,306,500	0.11

Notes: ${}^{\Delta}S_L$ @ 5% of *Cp*. *OM @ 5, 7, 10, 12, 15 and 18% of Cp (¥137,250 = ¥2,745 × 50). [a]The daily production was observed as 670 ml (≈ 5.15 $\mathrm{L/m^2\,d}$) for a TSS on 15/7/2008 in Fukui, Japan. The cost of feed water is neglected. $n = 5$ years and $d = 300$ days.

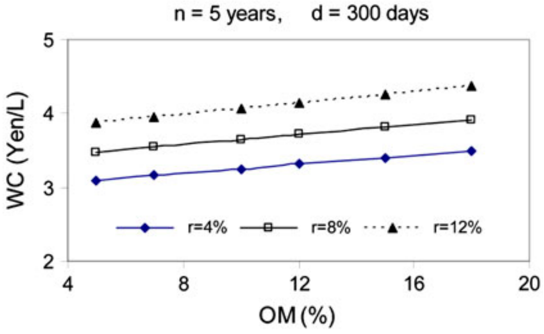

Fig. 4. Variations of water costs with different operational and maintenance costs.

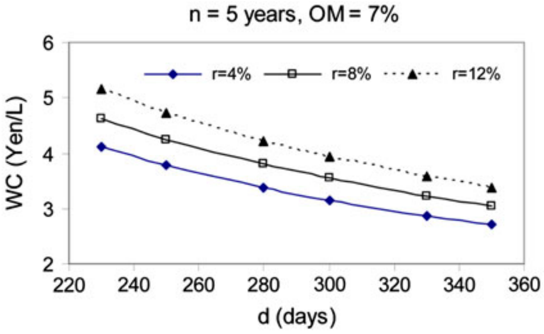

Fig. 5. Variations of water costs with different number of clear days in a year.

5.3. Cost payback periods

Fig. 6 shows the variations of the CPP with the different *Ps*. If *Ps* is increased from 30 to 130¥/L then the CPP reduces from 176 to 40 days (in average), respectively. This reveals that the CPP is greatly influenced by *Ps*. However, *r* has a negligible effect on the CPP in this case. Fig. 7 presents the variations of the CPP with the different *d*. The CPP is dropped from 68 to 45 days due to the increase of *d* from 230 to 350 days (in average), respectively. In addition, *r* also slightly affects the CPP. It is, therefore, concluded from the figures (Figs. 6 and 7) that the *Ps* and *d* have a significant effect on the CPP.

5.4. Relationship between production and solar radiation

Fig. 8 shows the relationship between M_{pd} and R_{sd} obtained in Fukui, Japan and Muscat, Oman. It indicates that m_{pd} is almost in proportion (linearly) to R_{sd}. It is deduced that the solar radiation is the most influential parameter on the productivity.

In addition, it was observed that the relative humidity of the humid air inside the TSS was definitely not saturated in the daytime from both experimental results (Japan and Oman) but was almost saturated (i.e. 100%) at nighttime. Therefore, the incorporation of the humid air properties in the

Table 4
Cost of distilled water for various designs of solar still

Researchers	Year	Cost ($\$/\text{m}^3$)	Remarks
Fath et al. [36]	2003	30	Pyramid solar still
Kumar and Tiwari [31]	2009	70.5*	Single-sloped passive solar still
This study	2013	31[a]	TSS

Notes: *This cost is varied from 1.54 to 4.01 Rs/*L* (i.e. 39–102 $\$/\text{m}^3$) which depends on r, OM, *d* and *n*; \$1 ≈ Rs 39. [a]When OM = 5% of *Cp*, $d = 300$ days, $n = 5$ years and $r = 4\%$ (with consideration to the labor cost).

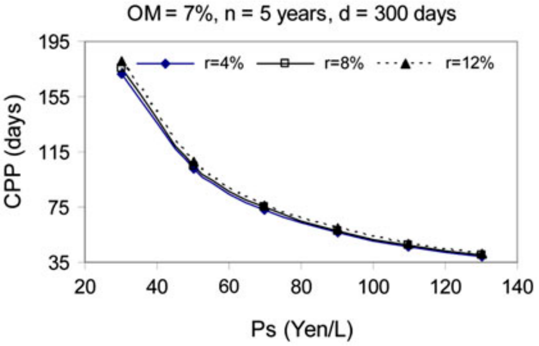

Fig. 6. Variations of CPPs with different water selling prices.

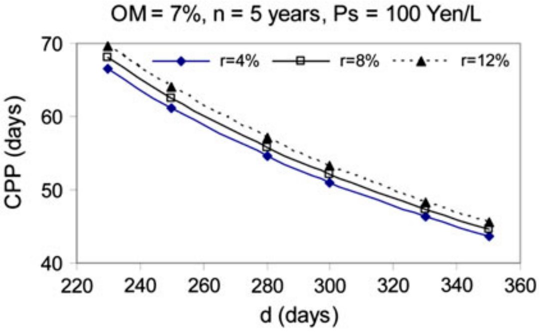

Fig. 7. Variations of CPPs with different number of clear days in a year.

numerical heat and mass transfer modeling should be required to predict not only the evaporation but also the condensation in solar stills.

6. Conclusions

In this study, a detailed estimation of the fabrication cost, WC, and CPP of the TSS were described. A few key factors that affect the WC and the CPP were identified. The WC was dropped by 35% (in average) when the number of sunny days (*d*) were increased from 230 to 350 days. If the operation and maintenance cost (OM) were increased from 5 to 18% of the capital cost, the WC increases by 12.4% (in average). It was observed that the *d* and OM greatly affected the WC. Additionally, the water selling price (*Ps*) and *d* had a significant effect on the CPP. If *Ps* was increased from 30 to 130¥/L, then the CPP reduces from 176 to 40 days (in average), respectively. The fabrication cost of the TSS was about \$13 and the WC was about $\$31/\text{m}^3$ with consideration to the labor cost, which is much lower than the single-sloped passive solar still. In developing and under-developed countries, when the prices of the materials and the labor cost become lower, it is, therefore, inferred that the WC would be reduced by at least one-third in those countries. Finally, a linear proportional relationship was found between the daily solar radiation and the daily water production fluxes of the TSS.

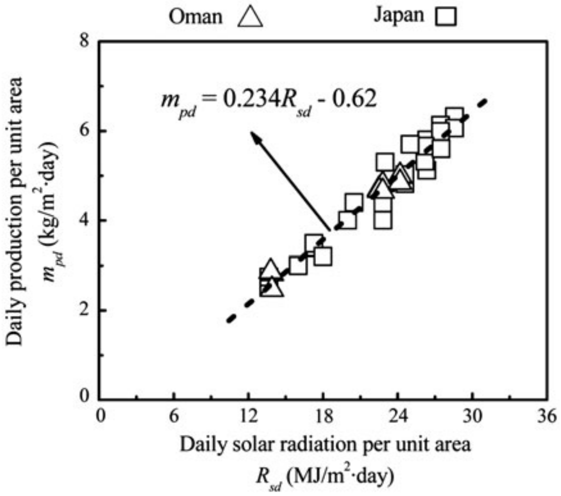

Fig. 8. Relationship between daily production flux and daily solar radiation flux.

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Symbols

AC — annualized uniform cost of the system (Yen)
CF — annual cash flow (Yen)
C_p — present capital cost of the system (Yen)
CPP — cost payback periods (years)
C_{RF} — capital recovery factor
C_{SF} — sinking fund factor
d — number of clear (sunny) days in a year (days)
LCC — life cycle costing
M_{pd} — daily water production flux ($\mathrm{kg/m^2\ d}$)
n — number of years/designed life of a TSS (5 years)
N — number of TSS (50)
OM — annual operational and maintenance cost of TSS (Yen)
P_s — water selling price (Yen/L)
$\mathrm{R_{sd}}$ — daily solar radiation flux ($\mathrm{MJ/m^2\ d}$)
r — bank benefit rate per year (%)
S_L — salvage (scrap) value of different components of TSS (Yen)
TSS — tubular solar still
W — annual yield (L)
WC — water production cost (Yen/L)

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