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Qualityand economic analysis of a double sloped solar still for household use in Kilifi County, Kenya

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Abstract: Kilifi County, Kenya has encountered persistent water problems due to many factors like rapid population growth, poor maintenance of existing water supply networks, water salinity due to seawater intrusion, pollution from numerous pit latrines and septic tanks in the towns , high levels of humidity and temperature which causes dehydration to the residents.Solar energy is clean, unlimited and very economic source of energy available to residents free of charge. Neither is sea water scarce in Kilifi due to its proximity to the Indian Ocean nor brackish water from boreholes and wells due to high water table levels. Double slope solar still uses the principle of evaporation and condensation to produce distilled water.The designed double slope solar still hada basin area of 1m^{2}and glass cover inclined at 15^{0}withan orientation in north-south direction. Materials used for fabrication were block board and normal window glass of 4mm which are locally available. An experimental investigation on a double slope solar still was carried out to examine the quality of water underKilifi county climatic conditions. Ambient temperatures, solar irradiation, relative humidity and water output were recorded. Water samples were analyzed for physical, chemical and bacteriological parameters (appearance, color, odor, pH, total alkalinity, total hardness and chloride content). The results obtained agreed with the standard values as prescribed by WHO and Kenya standards.The fabrication cost was found to be Kshs 9,350 with economic analysis showing that the designed and fabricated double slope solar still is an economic viable and feasible project with high Internal rate of return, saving to investment ratio ,positive net present value and a short payback period of less than 6 months. The double slope solar still is found to produce safe and clean water at a cheap cost ofaround Kshs 4.89 per liter andthus recommended for use inthe local households.

Keywords: Distillate, double slope solar still, economicanalysis, solar irradiation, water desalination, water quality.

Introduction

Coastal region are hot and humid and in constant demand of fresh water. Brackish water and Seawaterdesalinationhas beenconsideredasalong-termfreshwatersource. It is consideredasaviablesolutiontodrinkingwateralloverthe worldandKilifiCounty is not anexception.

Kilifi County has encountered persistent water problems due to many factors like rapid population growth and poor maintenance of existing water supply networks. Although the area is geologically rich in groundwater which is often seen as an option, exploitation is limited due to salinity because of seawater intrusion (Musingi*et al.*, 1999). Ground water exploitation is also curtailed by pollution from numerous pit latrines and septic tanks in the towns. In fact it has been revealed that more than 50% of all the diseases reported in the county are associated with lack of access to clean or good quality water and inadequate wastewater management (Munga, 2002).It is worth noting that the new excise duty act, number 23 of 2015 which came to effect 1st December 2015 (www.kenyalaw.org) increased the price of water by Kshs 10 per liter.

To address the limitations double slope solar still was designed and fabricated for desalination at household levels using locally available materials. The water output from the double slope solar still needs to be assessed for quality in terms of chemical and bacteriological contamination.Thestudy thereforeaimed to evaluate the economic analysis and viability as well as water quality from the designed and fabricated double slope solar still inKilifi County. Figure 1 shows the fabricated solar still.

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Figure 1: Fabricated double slope solar still

Water quality from solar stills

The salt contents present in the water not only cause bad taste but it also creates stomach problems and laxatives effects (Sukhatme, 1987).Solar still not only achieve the desired limit of 500 ppm but it also removes pathogens, nitrates, iron, chloridesand toxic heavy metals like lead, arsenic,cadmium and mercury completely (Al-Hayek and Badran, 2004 ;Zein and Al-Dallal., 1984). The process also proved to be effective in the destruction of microbiological organisms present in the feed water (Al –Hayek and Badran, 2004). The distillate is thus high purity water, which also lacks essential dissolved minerals.Drinking demineralised water can have serious health consequences, and it is thus of crucial importance that the essential minerals are added to the water before consumption (WHO, 2004). The advised quantities of minerals where minimum or no adverse health effects are observed are shown in Table 1.

Table 1: Advised mineralogical quantities (WHO, 2004)

	Total dissolved solids (mg/l)	Bicarbonates ions (mg/l)	Calcium (mg/l)	Magnesium (mg/l)	Hardness (mmol/l)	Alkalinity (meq/l)
Minimum	100	30	20	10		
Optimum	250-500		40-80	20-30	2-4	
Maximum						6.5

Storing distilled water with rainy water re-minerises the water. If the water seems to be too low on certain minerals, it is possible to re-mineralise it in an affordable and simple way by dissolution of natural occurring minerals (Hasson and Bendrihem, 2006; Ruggieri*et al.*, 2008).

Cost of the stills and water from solar still

Many factors affect the cost of distillate obtained from a solar desalination unit. Both capital and running costs are influenced by unit size, site location, feed water properties, product water required, quality, staff qualification and availability, etc. The main economic advantages of solar desalination are that it does not require much infrastructure, and it is simple to locally design, install, operate and maintain. The better economic return on the investment depends on the production cost of the distilled water and its applicability (Fath*et al.*, 2003;Kumar and Tiwari 2004;Govind and Tiwari,1984). The life cycle cost analysis should be done in order to make economic viability comparison with other designed and fabricated double solar stills for economic analysis (Kudish, *et al.*, 1986; Tiwari, G.N., 2011;Garg and Prakash, 2000;Solanki Chetan Singh, 2009).

The CRF (capital recovery factor), the FAC (fixed annual cost), the SFF (sinking fund factor), the ASV (annual salvage value), average annual productivity (M) and AC (annual cost) are the main calculation parameters used in the cost analysis of the desalination unit.

The AMC (annual maintenance operational cost) of the solar still required are regular filling of brackish water, collecting the distilled water, cleaning of the glass cover, removal of salt deposited (scaling). As the system life passes on, the maintenance on it also increases. Therefore, 10% of net present cost can be considered as maintenance cost (assumption). Finally, the CPL (cost of distilled water per liter) can be calculated by dividing the annual cost of the system (AC) by annual yield of solar still (M). The above mentioned calculation parameters can be expressed as follows:

i. Capital Recovery Factor (CRF):

$$CRF = \frac{i(1+r)^n}{((1+i)^n-1)} \text{.......................} 1$$

Where i= interest rate, n = number of useful years

ii. Hence the first annual cost (FAC)

$$FAC = CRF * P \text{ ....} 2$$

iii. Annual Salvage Value:

The sinking fund factor (SFF) for a system is given by :

$$SFF = \frac{i}{((1+i))^n-1)} \text{...................................} 3$$

iv. Therefore, if the salvage value of the system is S then, Annual salvage value(ASV)

$$ASV = (SFF) * S \text{.........................} 4$$

S =0.2 P (assuming 20% of present value as salvage value no reuse of salvage materials)

Further, the system requires some maintenance and it is a varying quantity, therefore the annual maintenance cost should also be considered.

$$\text{AMC} = 0.15 * \text{ FAC (Assuming 15\% cost of fixed annual cost)................} 5$$

(iii) Annual Cost/m = [First annual cost + annual maintenance cost –annual salvage value]

(iv) Annual yield = daily output yield (l) x365 days

(v) Annual cost/L (CPL)= [Annual first cost/ Annual yield]

Assuming the reuse of various components even after the useful life of the system is over; the salvage value can be estimated to be 35% of the initial cost, useful life 10 years, interest rate 12% and maintenance cost as 15% of annual first cost. Where P is the present capital cost of desalination system; i is the interest per year, which is assumed as 12%; n is the number of life ears, which is assumed as 10 years in most analysis.Solar stills represent a low cost technology with low cost maintenance, which can be carried out by unskilled manpower (Tiwari*et al.*, 2003).

Economic viability analysis

The factors that influence the systems economic viability are the outputs and costs of thesolar still systems, the cost of alternative energy source, cost of operation and maintenance, and the geographic location of the system, i.e. solar intensity, environmental temperature and humidity.

The net present value method used for cost analysis is a comparison between the investments made at present using the present value of money considering interest rate over a period of time. The net present value analysis was made according to equation 6(Wolpert, 2003).

$$NPV = I_o + \sum_{j=1}^{t} \frac{F_t}{(1+i^t)} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots 6$$

Where: *I*= capital cost, *F*= running cost, *i*= interest rate, *t*= time in years

The net present value (NPV), usually shows sum of the present worth of the cash flows within the considered analysis period, results > 0 validates the project as being economically feasible.

The Savings-to-Investment (SIR)evaluates the ratio of the savings to investment, where result = 1 shows that the initial cost is totally recovered, results > 1 shows that the savings will be more than and results < 1 shows that the cost would be greater than savings over the analysis period.The Internal rate of return (IRR) is the discount rate that makes the net present value of the initial investment equal to zero.

Materials andMethods

The data was gathered from 19.09.2016 to 19.10.2016 under the local weather conditions of Kilifi County (35.12° N latitude and 33.95° E longitude). The double slope solar stills wasrefilled withwaterthrough thefillingholeupto alevelof20mm.Between08:00am and 4:00 pm hourlymeasurementswere recorded.The doublesslope solar stillswasplaced in North-South direction orientation. The double slope still was tested using brackish water and damp proof black polythene paper as absorber plate.

To ensure water quality in terms of cleanness the still was rinsed with collected distilledwater. Wateranalyses were conducted on different days in the Mombasa government chemistry laboratory using different samples. Physical and chemical parameters recorded were appearance, color ,odor, pH, total alkalinity, total hardness, Chloride content ,Electrical conductivity (EC), Salinity and total dissolved solids (TDS).Appearance, color and odor were recorded pre and post distillation by physical examination of the samples. pH was recorded on aelectronic digital meter. The instruments werecalibrated before the test. Total hardness, chlorides and alkalinity was recorded and analyzed by following Kenya standards procedure. Bacterial test and analysis was also carried out according to Kenya standards and parameters such as Escherichia coli (before distillation) and product water (after distillation by a solar still) were analyzed.A report on level of water contamination before and after distillation was developed.

RESULTS AND DISCUSSIONS

Water output (Yield) from the double slope solar still

The fabricated double slope solar still was able to produce 1.652 liters per day per square meter during the period which the study was conducted (September and October 2016).An extract of the data on 21st September, 2016 is shown in the table 2.

Table 2: Typical data collected on 21st September 2016

Time	cumulative solar sill outputs	still output (ml)	cumulative solar sill outputs (ml)	solar irradiation(MJ/ m^2)	cumulative solar irradiation(MJ /m^2)	dry bulb temperature	wind velocity (m/s)	relative humidity	weather -sky	Rainfal (mm)
8.00	25.50	318.75	318.75	8.94	8.94	26.3	4	66	sunny	nil
9.00	0.00	0	318.75	8.86	17.8	27.5	8	60	sunny	nil
10.00	1.20	15	333.75	11.43	29.23	28	6	59	sunny	nil
11.00	4.30	53.75	387.5	12.02	41.25	28	8	60	sunny	nil
12.00	9.90	123.75	511.25	11.21	52.46	28.6	3	59	sunny	nil
13.00	17.60	220	731.25	12.5	64.96	28.7	6	56	sunny	nil
14.00	17.30	216.25	947.5	11.9	76.86	29	10	55	sunny	nil
15.00	15.00	187.5	1135	10.59	87.45	27.8	6	62	sunny	nil
16.00	10.50	131.25	1266.25	9.59	97.04	27.8	6	62	sunny	nil

Cost estimations
Anoverview of materialcost andtotalcost forthe double slope solarstill is shownin table 3

Table 3: material cost estimates

Sl.No.	Material	KSHs	USD$
1	Block board	3000	29.13
2	Labour costs-carpenter	2000	19.42
3	Polythene paper	500	4.85
4	Glass-4mm thick	3000	29.13
5	Paint 2litres	500	4.85
6	Collecting jar	100	0.97
7	Glueandsilicone	150	1.46
8	Plastic distillation channel/garden hose	80	0.78
Total		**9350**	**90.78**

1USD$ =ksh 103(as at 19^{th}, January2017 Central Bank of Kenya)

For cost effectiveness analysis, no consideration was made for certain costs such aspackaging and transport cost to the site. Other costs such as that of raw water andconcentrated salt disposal are not included (assumed to be zero). The total cost is 90.78USD$ and the cost could be lower when produced in large quantities for commercial purpose.

Calculation of simple payback Period
Daily distilled water production per unit area (mean) = 0.962 L/m^2/day
Cost of distilled water in Kenyan market = Kshs 50/L
Saving on distilled water produced everyday (gain) = 0.962 x 50 = Kshs 48.1/ day
Initial cost of present still = Kshs 9350/ m^2
So pay-back period of still is = 195days =0.5years

Economic analysis of designed and fabricated double solar still
Cost per liter of water
Annual yield = 0.96158Lx365= 351L
Annual cost/L= [Annual first cost/ Annual yield]

Assuming the reuse of various components even after the useful life of the system is over; the salvage value can be estimated to be 35% of the initial cost, useful life 10 years, interest rate 12% and maintenance cost as 15% of annual first cost. If the salvage value can be usedsalvage value can be estimated to be 20% of the initial cost.

Table 4: costs parameters

S.No	Parameter	Value
1	CRF	0.177
2	SFF	0.057
3	P	Ksh 9350
4	S	Kshs 3272.5
5	FAC	Kshs 1654.95
6	ASV	Kshs 186.53
7	AMC	Kshs 248.24
8	M(annual yield)	351L
9	cost/L	**Kshs4.89**

LCC analysis for the fabricated double slope solar still

Life Cycle Cost analysis (LCC) for modified solar still are given as:
Estimated annual clean water output = average daily output x 365 day
= 0.96158litres/day x 365days = 351 liters
The annual savings = annual output x water price (Kshs50/ liter), which is = Kshs 17548.84
Total annual savings = kshs 17548.84
The initial investment = Kshs 9350
analysis period =10 years
Discount rate = 4%
Table 5shows the result of the LCC analysis for the fabricated double slope solar still

Table 5:LCC analysis for the fabricated double slope solar still

Economic evaluation	Results
Net Present Value (NPV) in Kshs	**132,987**
Savings to investment Ratio(SIR)	**15**
Simple pay back (SP)	**0.5**
Internal Rate of Return (IRR)	**249.20%**

From the table above it is evident that:

i. NPV KSHS 132,987which is greater than zero hence the project is valid and economically feasible.
ii. Savings-to-Investment (SIR) is equal to 15which are greater than one hence the savings will be more than investment cost.
iii. pay-back period of still is 0.5years which is 195 days to recover initial investment cost average daylight hours of 6.9hours (2525hoursof sunlight per year)

The designed double slope solar still under Kenyan climatic condition (Kilifi County) with average daylight hours of 6.9hours (2525hours of sunlight per year) had an area of 1m^2, annual yield in litres (M) 0.962L, investment cost (P) Kshs9350 (USD$ 90.8) and cost per litre (CPL) of Kshs 4.89 (0.05 USD$).It is evident that cost per litres agrees very well with other designed solar stills. (Fath *et al.*,2003; Samee *et al.*,2007; Abdel-Rehim and Lasheen, 2007; Velmurugan *et al.*, 2008; Sadineni *et al.*, 2008; Elsebaii *et al.*, 2008; El-Bahi and inan, 1999; Badran and Tahaineh ,2005; Velmurugan and Srithar, 2007; Ismail, 2009; Kumar and Tiwari , 2004).

Water quality

The values of EC < 375 mS/cm was measured in the distilled water which is found to be within the standard ranges. The still was successful in removing pathogenic bacteria by more than 80%. These obtained parameters of the product water were then compared with various drinking water standards and found that most of the values obtained were within the acceptable ranges provided by the standards (World health Organization and Kenya bureau of standards). The distilled water was run through free air to allow re-minerisation. This had a detrimental effect as it may have come into contact with bacteria present in the air. In order to make the water safe and clean for drinking chlorination is advised as an option.Chlorine is easily available and at no cost from the Kenyan ministry of health at public health office all over the County. Chemically the water is found to conform to the standard set by World health Organization and Kenya bureau of standardson water quality.

Table 6shows a summary report from government chemist showing water quality in terms of bacteria and chemical properties.

Table 6: Waterparameters pre and post distillation process.

Parameter Date sample collected (values measured in PPM mg/L)	Borehole Sample 2 31/10/2016	Distilled water sample 1 21/09/2016	Distilled water sample 2 6/10/2016	Distilled water sample 3 31/10/2016	KEBS standards (maximum limits ppm)
Appearance	Clear	Clear	Clear	Clear	-
Color (hazen units)	10	10	10	16	-
Deposits	NIL	NIL	NIL	NIL	-
Odor	Unobjectionable	Unobjectionable	Unobjectionable	Unobjectionable	-
Turbidity (NTU)	0.54	0.4	3.77	16.2	2500
Electrical conductivity at 25^{o}C(μohms/cm^3)	972	156	52.9	375	-
Free carbon dioxide	50	0.8	38	1.0	0.5
Free saline ammonia nitrogen(N)	-	-	-	-	2.2
Phosphate PO^{-3}_4	0.41	1.54	0.96	0.1	1.5
Fluorides	-	1.11	-	-	1
oxygen absorbed ,four hours 27^{o}C(O)	0.8	0.8	0.8	0.8	-
Alkalinity as CACO3 Phenolphthalein (carbonate)	NIL	272	NIL	NIL	-
Methyl Orange (Bicarbonate)	380	132	44	16.0	300
Carbonate hardness as calcium carbonate ($CACO_3$)	-	240	-	-	300
Non Carbonate hardness as calcium carbonate ($CACO_3$)	-	NIL	-	-	-
Chloride ($CL^{-)}$	84	32	20	8.0	250
Nitrates(/NO^{-2}N)	0.5	0.26	0.07	0.4	35
Heavy metal(Cu)	-	0.03	-	-	2
Sodium(Na)	69	3	10	2.0	200
Potassium(K)	3	1	1	2.0	100
Calcium(Ca)	0.38	0.26	1.54	1.7	150
Magnesium(Mg)	2.31	1.83	1.25	1.9	100
Total Dissolved Solids ,residues dries at 180^{o}C	660	44.3	36	26.0	1000
PH	6.9	5.7	6.28	6.7	6.5-8.5
Total Coliform Count (MPN/100ml)		>2400	>2400	>2400	NIL

Faecal Coliform(E.coli) Count (MPN/100ml)		53	91	3	NIL
Total plate count(37^{o}C,48 hours)cfu/ml		48			20

Conclusions and recommendations

From the results of the study conducted (September and October 2016) it is evident that the water extracted from the collecting jar was within the range of themineralogical advised qualities but found to be bacteriological contaminated .This bacteriological contamination could have arisen from sanitation and handling of double slope solar still or from environmentally trapped bacteria in the air .The water can be made safe for drinking by use of chlorination where chlorine is given freely at public health departments all over the coastal region. To improve mineral content the distilled water can be remixed with other clean and safe drinking water like rain water. The total cost of the double solar still is 90.78 USD$ and the cost could be lower when produced in large quantities for commercial purpose.

The LCC analysis shows that NPVisKshs 132,987which is greater than zero hence the project is valid and economically feasible,Savings-to-Investment (SIR) is equal to 15 which are greater than one hence the savings will be more than investment cost and pay-back period of still is 0.5years which is 195 days to recover initial investment cost.The payback period for the double slope solar still is less than one year.Thestudy has also revealed that the annual cost per liter was approximately Kshs 4.89 which ensures the acceptability of passive double slope solar still in rural and economically challenged areas since the retail market price for clean and safe water in the region is Kshs 50 per liter.

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