Chapter

Modeling of Solar-Powered Desalination

Zafar Abbas, Nasir Hayat, Anwar Khan and Muhammad Irfan

Abstract

The scarcity, global, and local demand of pure water for SDGs become prominent issue. The global emissions of CO2 and GHGs have put pressure to develop the solar-powered desalination plants. This article discussed the selection of site for the solar thermal desalination in Pakistan keeping the eye on sustainability and modeling and cost analysis of single solar stills technology at Lyari River in Karachi, Pakistan. Pakistan is among the water-deficit countries having 35% of population having lack of pure drinkable water. The plenty of solar irradiance and saline water in Pakistan make it very favorable for solar-powered desalination. The solar stills technology is one of the best technologies to meet the local demand of pure water. The modeling is composed of governing equations based on the law of conservation of mass and law of conservation of energy. The solar irradiance at Lyari River is taken from MERRA–2. The result depicted that the hourly production of distill water is 1 kg/m^3 and 8 kg/m^3 with and without the FRL lens. The cost of distill water produced from the solar stills having FRL lens is 33% less as compared with solar stills without FRL lens.

Keywords: SDGs, GHGs, desalination, solar powered, solar stills

1. Introduction

Water is the resource that sustains all life on the planet earth and key element of sustainable development [1]. The rapid growth in population, and industrial and economic development needs high demand of water. The need of freshwater for drinking and potable water in arid areas is increasingly important issues in most part of the world. In 2000, the world annual demand for water is 4000 billion cubic meter. By 2030, it is estimated to increase over 58% [2]. Water availability per person in Pakistan was 5,600 cubic meter in 1960, and it is reduced to 1000 cubic meter in 2018. The demand of water in Pakistan is important because of its agrarian nature of economy and the agriculture sector shares 24% of gross domestic product (GDP). The regional conflicts on the availability and use of water have pressure on the demand of water. The water sources in Pakistan are surface water, rainfall, glaciers, and groundwater. Surface water consists of rivers, lakes, dams, and runoff during and after heavy rains. Mostly, the groundwater is the source in urban areas except in Karachi, Hyderabad, and some part of Islamabad use surface water. Water for rural areas is also from groundwater source except in saline groundwater areas where irrigation canals are used for domestic purpose [3]. Currently, the water availability per capita in Pakistan is 1000 cubic meter. According to Population Action International, 1993, the countries with water availability below 1000 cubic meter experience chronic water stress [1]. Presently, more than 65% people of total population have access to safe drinking water including 85 and 55% urban and rural areas, respectively. The 35% of population has lack of drinkable water in Pakistan [3]. According to WHO, a drinkable water should have dissolved salt concentration less than 500 ppm. The normal seawater and brackish water have dissolved salt and ion concentration of 3500 ppm and 1000 ppm. Therefore, desalination of seawater and brackish water is the way to make the water drinkable. Most of the desalination plants use conventional methods of energy. But the fossil fuel methods of energy sources have adverse impact on environmental sustainability by producing air pollution, global warming, and GHGs emission. The utilization of fossil fuels for the desalination plants is contributing in CO_2 emissions. The total installed power plant for the desalination processes is responsible for the emission of 76 million tons (Mt) of carbon dioxide per year. In 2040, the emission of CO_2 is expected to 218 million tons per year [4]. The cuse of fossil fuels for desalination plant is neither sustainable nor environment friendly. Therefore, there is a need of alternative sources of energy to achieve the world demand of freshwater. At a same time, the alternative source should be sustainable and environmental friendly. The renewable energy sources of energy are the alternatives to power desalination processes. Thus, the solar power desalination is one of the most suitable alternatives for desalination plant that meets water demand and also environmental friendly.

Therefore, in this research paper the focus is on the demand of water in Pakistan as the result of rapid growth in population and industrialization. It has become necessary to install the desalination plant in Pakistan by keeping in mind the energy available as well as economic situation. The main ambitions of this research are to select a site having plenty of solar radiations and salt or brackish and suitable solar technology having low capital and operational cost to fulfill the demand of pure water at minimum cost. Thus, the development of mathematical model of solar stills and cost analysis at Lyari River, in Karachi, follows the solution of mathematical model using MATLAB.

2. Methodology

The methodology of this research is composed of the selection of site in Pakistan for solar power desalination following the mathematical modeling of the single slope of solar stills and employs modern software for the solution of mathematical model. The governing equations for mathematical model of the solar stills are based on the law of conservation of mass and law of conservation of energy for the system. The equations for convective heat transfer coefficients and radiation heat transfer coefficients are based on the Dunkle's model. The MATLAB r2019 is employed to solve the equations.

2.1 Site selection in Pakistan

The availability of **1900–2200 kWh/m^2** annual global irradiance makes Pakistan highly favorable for solar power-based desalination [5]. The Balochistan and Sindh province of Pakistan is rich in solar energy with an average daily direct normal irradiance of 5.3–5.6 kWh/m^2 and 2.5–3.0 kWh/m^2 with sunshine duration of 8–8.5 hours a day [6]. Therefore, in this research paper the site at Lyari River Karachi has been selected for the modeling the single-slope solar stills.

2.2 Mathematical modeling of solar stills

The basic assumptions while modeling the solar stills take negligible temperature stratification within the evaporator basin. Temperature is uniform within each still component. Temperature is time dependent. The evaporated water is assumed only pure water; that is, the evaporated water has no dissolved salt or ion. The stills have no vapor leakages. The governing equations are based on law of conservation of mass and law of conservation of energy. The schematic of single slope solar stills is shown in **Figure 1**.

The law of conservation of mass can be written as [7].

$$\dot{m}_{sw} = \dot{m}_{ev} + \dot{m}_b \tag{1}$$

If **Xsw** is the concentration of salt in the feed saline water, **Xb** is the concentration of salt in the cbrine within the basin. Then, the salt balance is [7].

$$\dot{m}_{sw}X_{sw} = \dot{m}_b X_b \tag{2}$$

The solubility of salt determines the salt content in the brine. The salt content in the brine is important in practice to avoid the problem of forming layer and blockage. The factor ***fc*** for concentration is defined as the ratio of brine concentration to feed concentration.

$$fc = \frac{X_b}{X_{sw}} \tag{3}$$

This factor is used to fix a threshold limit to not exceed during evaporation and condensation. By solving Eq. (2)) and Eq. (3), we have the following equation.

$$\dot{m}_b = \frac{1}{fc}\dot{m}_{sw} \tag{4}$$

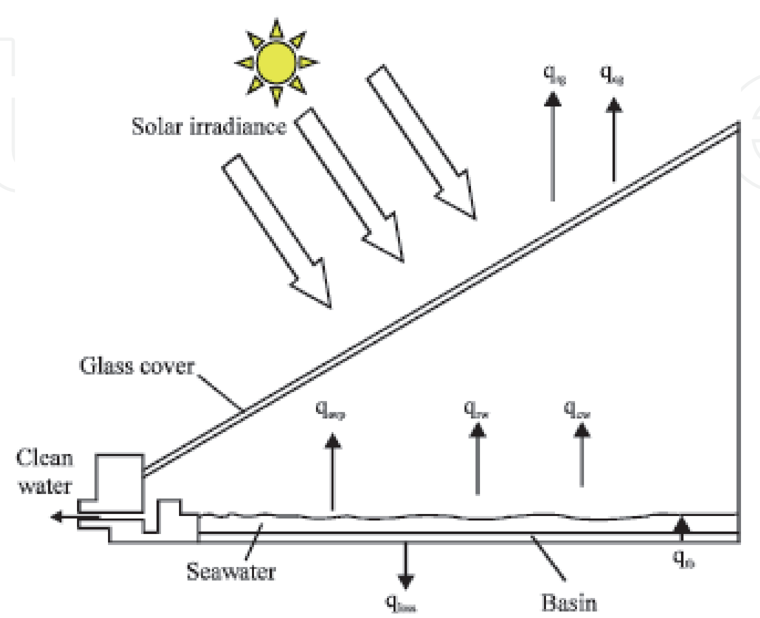

Figure 1.
Schematic of single-slope solar stills.

$$\dot{m}_{ev} = \frac{fc - 1}{fc} \dot{m}_{sw} \tag{5}$$

Eq. (5) is for the stationary conditions, the rate of evaporated water as a function of rate of feed saline water. Now, the distillated water or recovery rate can be defined as

$$\varphi = \frac{fc - 1}{fc} \tag{6}$$

The recovery rate is an important parameter, which indicates the possible amount of distillate water from the saline feed water without scaling [7]. It means that only 40% of saline water can be transformed into distillate water without encrustation and blockage.

The law of conservation of energy gives the following set of equations for the respective components in the solar stills.

The energy balance equation for the outer of the transparent glass cover is as follows [7]:

$$\frac{\rho_g V_g C_{p,g}}{2A_g} \frac{dT_{ge}}{dt} = \frac{\lambda_g}{e_g} \left(T_{gi} - T_{ge}\right) - hc_{ge-am} \left(T_{ge} - T_{amb}\right) - hr_{ge-sky} \left(T_{ge} - T_{sky}\right) \tag{7}$$

The energy balance equation for the inner of the transparent glass cover is as follows:

$$\frac{\rho_g V_g C_{p,g}}{2A_g} \frac{dT_{ge}}{dt} = \acute{\alpha}_g I(t) + \left(hc_{sw-gi} + hr_{sw-gi}\right) \left(T_{sw} - T_{gi}\right) + \frac{\dot{m}_{ev} L_v}{A_g} - \frac{\lambda_g}{e_g} \left(T_{gi} - T_{ge}\right) \tag{8}$$

The energy balance for the seawater inside the basin of solar still is as follows [7]:

$$\frac{\rho_{sw} V_{sw} C_{p,sw}}{A_{sw}} \frac{dT_{sw}}{dt} =$$

$$\acute{\alpha}_{sw} I(t) + hc_{c-sw}(T_c - T_{sw}) + \frac{\rho_{sw} D_{sw}}{A_{sw}} \left(c_{p,sw} T_{sw,in} - c_{p,b} T_{b,out}\right) - \frac{\dot{m}_{ev}}{A_{sw}} \left(h_L - c_{p,b} T_{b,out}\right) - \left(hc_{sw-ig} - hr_{sw-ig}\right) \left(T_{sw} - T_{gi}\right) \tag{9}$$

The convective heat transfer coefficient of between the outer of the transparent glass cover and the ambient temperature depends on the wind velocity. According to McAdams correlation [8], this coefficient is approximated by the following equation.

$$hc_{ge-amb} = \begin{cases} 5.621 + \dfrac{1151.2v}{T_{amb}} if v < 4.88\ ms^{-1} \\ 604.29 \left(\frac{v}{T_{amb}}\right)^{0.78} if\ 4.88 \le v < 30.48\ ms^{-1} \end{cases} \tag{10}$$

The heat transfer coefficient between the saline water and the inner of the transparent glass cover is given by the second form of Dunkle's model and can be written as [9].

$$hc_{sw-gi} = 0.884\left(T_{sw} - T_{gi} + \frac{\left(p_{sw} - p_{gi}\right)T_{sw}}{2.689 \times 10^5 - p_{sw}}\right)^{\frac{1}{3}} \quad (11)$$

The radiation heat transfer coefficient between the outer of the transparent glass cover and the sky is given by

$$hr_{ge-sky} = \varepsilon_v \sigma\left(T^2{}_{ge} + T^2{}_{sky}\right)\left(T_{ge} + T_{sky}\right) \quad (12)$$

σ is the Steffen Boltzman constant.

The sky temperature is determined by [10].

$$T_{sky} = T_{amb}(0.74 + 0.006\theta)^{0.25} \quad (13)$$

Where Θ is the dew point temperature given by [11].

$$\theta = \frac{273.3}{17.27 - In\varepsilon + \frac{17.27T_{amb} - 4061}{T_{amb} - 35.85}}\left(In\varepsilon + \frac{17.27T_{amb} - 4061}{T_{amb} - 35.85}\right) \quad (14)$$

ε is the relative humidity.

The radiation heat transfer coefficient between the saline water and the sky is expressed as

$$hr_{ge-sky} = \varepsilon_{eff} \sigma\left(T^2{}_{sw} + T^2{}_{gi}\right)\left(T_{sw} + T_{gi}\right) \quad (15)$$

Emissivity is given by,

$$\varepsilon_{eff} = \left(\frac{1}{\varepsilon_{sw}} + \frac{1}{\varepsilon_g} - 1\right)^{-1} \quad (16)$$

The equation in the second part of the (Eq. (9)) in given by Dunkle's model as [9].

$$\dot{m}_{ev} h_L = h_{ev} A_{sw}\left(T_{sw} - T_{gi}\right) \quad (17)$$

The latent heat of vaporization $\mathbf{h_L}$ is given by [9].

$$h_L = 3146 - 2.36T_{sw} \quad (18)$$

The evaporative heat transfer coefficient h_{ev} is given by [9].

$$h_{ev} = 0.016273\, hcv_{sw-gi} \frac{p_{sw} - p_{gi}}{T_{sw} - T_{gi}} \quad (19)$$

The evaporative heat transfer coefficients Eq. (11) and Eq. (19) can only be estimated through correlations when the following conditions is satisfied: the aspect ratio $2.5 \le a \le 5.5$, the inclination angle $10^0 \le i \le 30^0$, and Rayleigh number $5 \times 10^6 \le Ra \le 5 \times 10^7$.

If the above conditions are not fulfilled, then it could be done either experimentally or by using 2D modeling of the problem such as considered in some other systems [12, 13].

The Nusselt number is obtained through a correlation in the form by to express the convective heat transfer coefficients [14].

$$Nu = c(Ra)^n = c(GrPr)^n \tag{20}$$

The Grashof and Prandtl number is given by,

$$Gr = \frac{\beta g \rho^2 L^3 \triangle T}{\mu^2} \tag{21}$$

$$Pr = \frac{\mu c_\rho}{\lambda} \tag{22}$$

The correlation that gives Nusselt number is [14].

$$Nu = \begin{cases} 1 \, if Gr < 10^5 \\ 0.5(Ra)^{0.25} if \, 10^5 < Gr < 2 \times 10^7 \\ 0.15(Ra)^{0.33} if Gr > 2 \times 10^7 \end{cases} \tag{23}$$

When the Nusselt number is known, the heat transfer coefficient between the basin liner plate and the saline water can be calculated for an active solar still as

$$hcv_{c-sw} = \frac{Nu_{c-sw} \lambda_{sw}}{L} \tag{24}$$

The convective heat transfer coefficient between the fluid and the plate for an active solar still is calculated as [15].

$$hcv_{h-c} = \frac{Nu_{h-c} \lambda_h}{L} \tag{25}$$

The heat loss coefficient is approximated by the following equation [15].

$$U_{loss} = \frac{\lambda_{is}}{e_{is}} \tag{26}$$

$T_{b,out}$ can be assumed to be equal to that of the plate T_p for larger length of basin liner for an active solar stills [15].

The MATLAB's solver for ordinary differential equations (ODEs), MATLAB ode45 function, has been employed for the efficient computation of the differential equations.

The material properties and dimensions of solar still are given in **Table 1** and thermophysical properties of glass, basin, and insulation are given in **Table 2** in Appendix A.

3. Results

The hourly production of distill water in $kg/hour$ at Lyari River, Karachi, with and without Fresnel (FRL) lens. The results are depicted in **Figure 2**.

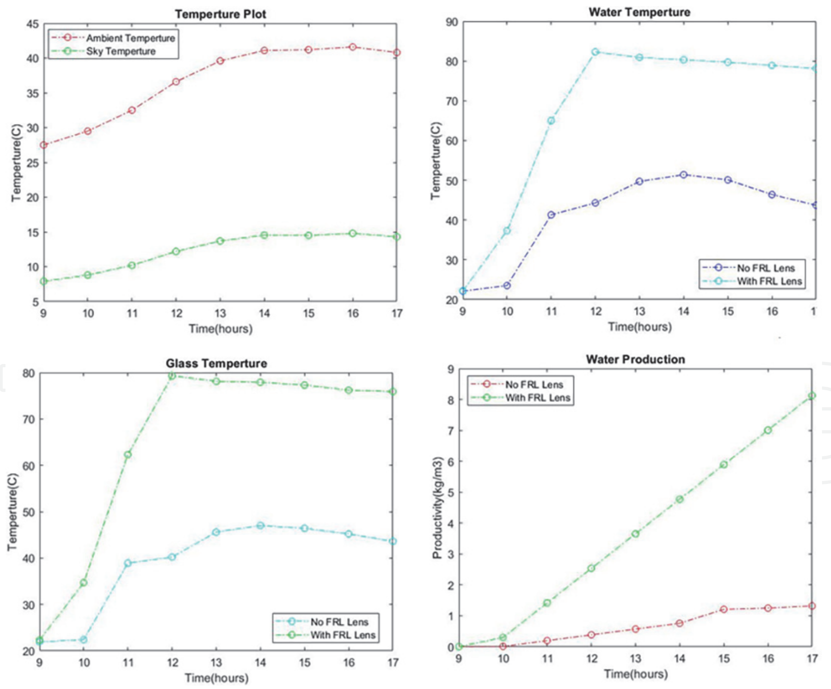

Figure 2.
Result of mathematical model of single slope solar still.

The maximum ambient temperature and sky temperature on the hottest day is 39.5°C and 14.7°C. The result is showing that the maximum water temperature with and without Fresnel (FRL) lens is 82.3°C and 47.2°C. And also the maximum glass temperature with and without FRL lens is found to be 80°C and 39.5°C. The production of water is calculated using the temperatures. The maximum water production with and without FRL lens is 8 kg/hour and 1 kg/hour. Using FRL lens, the production of water is 330% more than without using FRL lens.

4. Cost analysis

The cost analysis of the solar still with and without FRL lens includes the capital, operational, and maintenance cost. The major contributor is FRL lens that cost 90$. The details of the costs are given in Appendix A.

The economic performance is estimated by the following.

$$P = \frac{Capital\ cost + Operational\ cost/year + Maintenance\ cost/year}{water\ production/year} \tag{27}$$

The monthly operating cost is about 1.25$. There is no maintenance cost is required in this case but only the cleaning cost. The accidental cost is not considered in this study. The cost with FRL is 122.3$ and without FRL is 22.27$. The production of distilled water per cubic meter with and without FRL is found to be 1.37$ and 1.66$, respectively.

5. Conclusion

It is concluded that the scarcity of pure water can be compensated by desalination processes to meet the global demand of water as some developing countries have already done. The developed and developing countries have the capacity to install the conventional source of desalination plant but this attitude is greatly impacting on the environmental issues such as global emissions of CO_2 and greenhouse gases (GHGs). Currently, the desalination plants are based on the conventional sources of thermal energy. The sustainable development goals (SDGs) can only be achieved using the renewable source of energy for the desalination processes. This will eliminate two main problems: global emissions and scarcity of water. The alternative and most effective source for desalination processes keeping in mind the SDGs is the solar thermal desalination processes. The capital and operational cost of the conventional thermal desalination processes are high enough that under developing countries cannot afford it. Therefore, the solar thermal desalination processes are the best option for those countries. The plenty of solar irradiance, water, and land make Pakistan the best suited area for the solar thermal desalination. Baluchistan, Sindh, and Southern Punjab are the most suitable area for the solar energy applications. The Lyari River at Karachi in Sindh province is one of the most suitable areas for the solar thermal desalination processes. The solar stills technology for the distillation of saline water is one of the most favorable technologies to distill water to meet the water demand of Pakistan at effective cost. The governing equations of mathematical modeling of solar still were based on law of conservation of mass and law of conservation of energy. MATLAB was employed to solve the governing equations of the mathematical model. The result is showing that the utilization of Fresnel (FRL) lens makes the solar stills more productive of distill water as compared with solar stills without Fresnel lens. At the same time, the cost of pure water is less while using FRL lens in the solar stills. The solar stills technology works more efficiently at the remote areas of Pakistan where high-cost desalination plants are far enough to install. And ease of installation, capital, operational, and maintenance cost make it possible to reach to all people.

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Conflict of interest

There is no conflict of interest for this publication.

Nomenclature

Symbols

A_{sw}	Area of saline water (m^2)
A_g	Area of glass cover (m^2)
A_b	Area basin (m^2)
A	Aspect ratio (dimensionless)
c	Constant in Nusselt correlation (dimensionless)
$c_{p,b}$	Specific heat of brine ($J\ kg^{-1}\ K^{-1}$)
$c_{p,sw}$	Specific heat of saline water ($J\ kg^{-1}\ K^{-1}$)
$c_{p,g}$	Specific heat of glass ($J\ kg^{-1}\ K^{-1}$)
e_g	Thickness of glass cover (mm)
e_{gs}	Thickness of insulation material(mm)
Fc	Feed concentration factor (dimensionless)
I(t)	Solar Intensity (Wm^{-2})
I_O	Constant solar intensity (Wm^{-2})
I	Inclination angle of glass cover (degree)
Gr	Grash of number
G	Acceleration of gravity ($m\ s^{-2}$)
Hl	Height of the higher side of the still (m)
Hr	Height of the lower side of the still (m)
H	Mean height of the still (m)
h_L	Latent heat of vaporization ($kJ\ kg^{-1}$)
h_{ev}	Evaporative heat transfer coefficients ($kJ\ kg\text{^}^{-1}$)
$hc_{ge\text{-}amb}$	Convective heat transfer coefficient between outer glass cover and ambient ($Wm^{-2}\ K^{-1}$)
$hc_{sw\text{-}gi}$	Convective heat transfer coefficient between saline water and inner glass ($Wm^{-2}\ K^{-1}$)
$h_{ge\text{-}sky}$	Heat transfer coefficient between outer glass cover and sky ($Wm^{-2}\ K^{-1}$)
$\dot{m}_{sw}$	Mass flow rate of Saline water ($kg\ m^{-3}$)
$\dot{m}_b$	Mass flow rate of brine ($kg\ m^{-3}$)
m_w	Mass yield hourly ($kg\ m^{-3}$)
$\dot{m}_{ev}$	Mass rate of produced vapor ($kg\ m^{-3}$)
Nu	Nusselt number (dimensionless)
N	Exponent in Nusselt correlation (dimensionless)
Pr	Prandtl number (dimensionless)
p_{gi}	Partial pressure of the water at the interior of the glass cover (Pa)
p_{sw}	Partial pressure at saline water surface temperature (Pa)
Ra	Rayleigh number (dimensionless)
T_{amb}	Ambient temperature (K)
$T_{b,out}$	Brine output temperature (K)
T_{ge}	Temperature at the outer side of cover glass (K)
T_{gi}	Temperature at the inner side of cover glass (K)
T_{sw}	Temperature of saline water (K)
$T_{sw,in}$	Inlet temperature of saline water (K)

T_{sky}	Sky temperature (K)
t	Time (s)
t_c	Time period for calculation of the yield (s)
U_{loss}	Loss factor per unit surface (W m^{-2} K)
V_g	Volume of glass cover (m^3)
V_{sw}	Volume of saline water (m^3)
v	Wind speed (m s^{-1})
w	Width of the solar stills (m)
x_b	Concentration of salt in brine (mg l^{-1})
x_{sw}	Concentration of salt in feed saline water (mg l^{-1})

Greek letters symbols

α_{c},	Fraction of solar energy absorbed by basin liner material (dimensionless)
α_{g}'	Fraction of solar energy absorbed by glass cover material (dimensionless)
α_{sw}'	Fraction of solar energy absorbed by saline water (dimensionless)
β	Coefficient of volumetric thermal expansion (K^{-1})
β_{sw}	Coefficient of volumetric thermal expansion for saline water (K^{-1})
ϵ_{eff}	Effective emissivity (dimensionless)
ϵ_g	Emissivity of cover glass (dimensionless)
ϵ_{sw}	Emissivity of saline water (dimensionless)
φ	Feed recovery rate (dimensionless)
Γ	Yield (kg)
λ	Thermal conductivity (W m^{-1} K^{-1})
λ_g	Thermal conductivity of glass cover (W m^{-1} K^{-1})
λ_{sw}	Thermal conductivity of saline water (W m^{-1} K^{-1})
λ_{in}	Thermal conductivity of insulation material (W m^{-1} K^{-1})
μ	Viscosity (N s m^{-2})
μ_{sw}	Viscosity of saline water (N s m^{-2})
ρ	Density(kg m^{-3})
ρ_g	Glass cover density (kg m^{-3})
ρ_{sw}	Saline water density (kg m^{-3})
σ	Stefan-Boltzmann^'s constant (5.6697×10^{-8}) (W m^{-2} K^{-4})
θ	Dew point temperature (K)
ε	Relative humidity (dimensionless)
ΔT	Temperature difference in transfer by natural convention (K)

Appendix A

Parameter	Value
Basin Area	0.2
Thickness	2
Basin Material	Aluminum
Insulation	Wool
Thickness	20
Channels	PVC
Glass	Tempered
Glass Area	0.234
Thickness glass cover	0.04
FRL Lens	R18
Lens Area	0.2839

Table 1.
Material properties of solar stills.

Parameters	Value
Basin absorptivity	0.90
Glass absorptivity	0.05
Water reflectivity	0.05
Glass reflectivity	0.05
Glass emissivity	0.94
Water emissivity	0.95
Specific heat	4.002
Glass thermal conductivity	1.03
Insulation thermal conductivity	0.0363
Water depth	0.02
Wind velocity	4.6

Table 2.
Thermophysical properties.

Cost(PKR)	Without FRL	With FRL
Capital	3550	19500
Operational	1200/year	1200/year
Maintenance	500/year	500/year

Table 3.
Cost of solar stills with and without FRL lens.

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