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Experimental Investigation of Water Purification Using Integrated Solar Energy System

AWASH TEKLE
Department of Mechanical Engineering, Aksum Institute of Technology, Aksum University,
Po.box: 1010 Aksum, Tigray, Ethiopia
Email: awashtek@gmail.com or awashtek@yahoo.com

ABSTRACT

The present research work was done to determine the performance and production rate of integrated solar energy use for water purification mechanism. The principal objective of the paper was to design integrated (modern solar energy (or photovoltaic) and solar thermal) water purification devices with low cost and high efficiency for rural remote applications. Heat transfer and efficiency of the conventional solar still and integrated solar still was analyzed based on the energy law of thermodynamics. According to the result obtained, the efficiency of conventional solar still and integrated solar still was 26.65 % and 29.61% respectively. And the efficiency of integrated grid power uses solar still desalination was 50.26%. The average water produced from integrated solar energy use and solar still was 7 liter and 1.8 liters respectively. The measurement of water chemistry was done for feedwater, pretreated, and post-treated; and the result was compared with WHO and other standards. The payback period of the conventional solar still and integrated water purification was 1.274 and 0.61 respectively, and the unit water purification cost was US $ 329.50 and the US $ 674.50 respectively and this economic result shows that the integrated solar still water purification was feasible for remote rural areas.

Keywords: Water Purification, Integrated Solar Energy, Solar still, Experimental investigation
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1. INTRODUCTION

Water is the most abundant and it covers 75 % of the earth's surface and from this 97.4 % is saline and polluted and 2.6 percent is sweet and freshwater (*A. Kasaeian et al. 2018*). The 2.6 percent (200000 km2) fresh and drinkable water resources on earth (including poles, groundwater, rivers, and lakes) are drinkable water and not enough (*H.K. Jani, K.V. Modi 2018, M.A. Al-Nimr, W.A. Al-Ammari 2016*). Based on the UN water development data, the worldwide population size that is affected by a lack of freshwater supply reaches 3.7 billion and this will increase by 2.3 billion people in 2050 (*F.E. Ahmed et al.2018*). Due to this, more than half of the total world hospital beds occupied by patients with easily prevented waterborne disease (*WHO 2011*). Water scarcity affects all over all parts of the continent and the pressure increases in developing (or low income) countries (F.E. Ahmed et al. 2018). Based on the WHO data, above half a million people worldwide die yearly because of the scarcity of drinkable water, and from these 80-90 percent of mortality comes from 88 developing countries (Hisham T. et al 1999, WHO 2011, R. Santosh et al.2019). And the demand increase from time to time due to the incrementing of population, agriculture and urbanization sectors; and climate changes.

Globally, improved water quality increases from 76 to 91 percent but in sub-Saharan countries (like Ethiopia) the gab remains huge (Temitope D. Timothy Oyedotun 2017). According to the 2011 data information, the total freshwater availability of Ethiopia is around 153 km3 and hugely available but many people suffered by using lakes, rivers, boreholes, and hand pumps and none of which are protected from any contamination (Temitope D. Timothy Oyedotun 2017, Abebe Tadesse Lencha 2012) and according to 2014 water organization survey says: 61 million people have lack of access to safe water and 65 million Ethiopian people have lack of access to use improved sanitation (Water organization survey 2018). Tigray water coverage in terms of access was 66 % and 62 % for urban and rural areas respectively, and that of hygiene and sanitation coverage was 34 % (Ayenew A., Meresa K. & Abdulkadir M. 2011). The unavailability of cost-effective and economical water treatment techniques makes the situation worse. Thus, due to public health and environmental concerns, the decontamination of water with effective and low-cost methods is very important (Singh, P. et al. 2018).

1.1 Water purification technologies

Water purification is a process that separates and purifies the feed water (like saline water, seawater, and brackish water) into drinkable water using water purification technologies. Water purification technologies may vary based on the type of technique they apply. However, they have in common because the driving force (directly or indirectly) of all techniques is solar radiation except sand filtration. And all these technologies are categorized as solar thermal (direct and indirect) and solar electric use technology (Fig. 1). Different water purification technologies developed by the researchers and these technologies may alone or using integrated mechanisms.

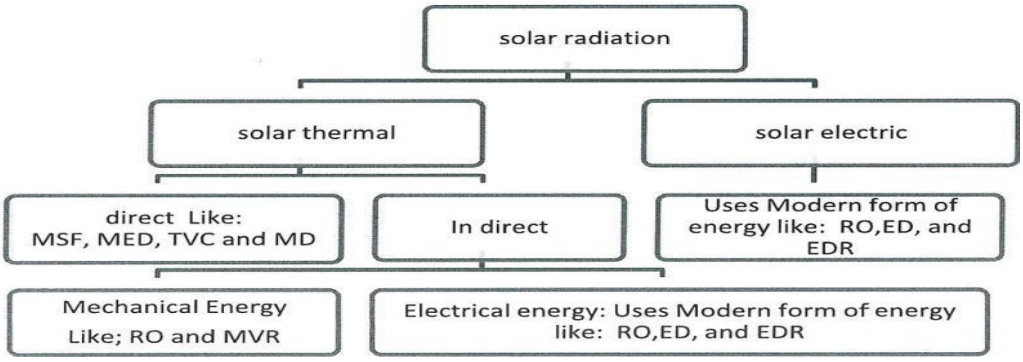


Fig.1: Classification of water treatment (Ahmed Alkaisi et al 2017)

Integrated water purification technologies have been used for performance improvement, cost minimization, and the reduction of environmental pollution. For the same purpose, different researchers work on it. Integrated renewable energy use desalination technology is win-win for purified water and energy (Ahmed Alkasi et al. 2017). A sustainable solution to desalination using integrated renewable energy (S. Manju, N. Sagur, 2017). Integrated solar desalination has developed using four solars still and humidification-dehumidification (S.W. Sharshir et al 2016). The integration of solar chimney and seawater desalination has been developed (L. Zuo et al. 2011). Thermodynamic analysis for the integration of solar chimney and desalination has been done (C. Mendez, Y. Bicer 2020). Efficient desalination using renewable energy supported technologies (N. Ghaffour et al. 2014). These all technologies were not economically feasible and large scale; and impossible to use small scale and in remote areas. From these, the simplest water purification technology, for remote rural areas, is an integrated solar still distillation (SSD) system since it is suitable and low cost (M.A. Abdelkareem et al 2018, Ahmed Alkaisi et al 2017). So, the main objective of the paper was to develop and investigate a new integrated solar energy water purification device; and the research aims to develop efficient, reliable, and inexpensive integrated solar energy use water purification technologies for the remote rural community of Ethiopia especially Tigray region.

2. MATERIALS AND METHODS

2.1 Materials and Description of the system

The construction and material availability of this hybrid water purification are simple and feasible for the remote rural community. The materials chosen were low cost, able to withstand high temperatures, safe, and effective regarding both the capture and retention of solar energy; and the materials used to manufacture the device. The proposed integrated water purification technology was manufactured at the mechanical department workshop using the locally available sheet metals, glass, gate valves, and rectangular and tabular tube; and for fast sand filtration, it used sand from fine to coarse (from bottom to the top stage) and it was simple semi membrane among each stage. This system consists of the airtight capacity to protect energy loss. This device consists of an absorber, glass, re-heater and condenser, nozzle, energy storage, sand with simple membrane, PV system, resistor, switch, convertor, and insulation system. Collector area (absorber): The incoming solar energy absorbed by the absorber and the total effective area of the collector is 1 m^2; and the width and length are 750mm by 1350mm respectively. And the absorbed energy by the absorber transfers to the water and insulation. The liner material selected should absorb most solar energy, watertight, durable, cleanable, and withstand temperatures around 100^0C. Asphalt matt is preferable as basin stills therefore, in shallow basin stills black butyl rubber. The purpose of the nozzle is to reduce the pressure within the system by converting the vapour pressurized energy to kinetic energy. And this conversion helps the vapour to run to the condenser system and reduces the pressure inside the still and boiling water temperature will be reduced. Pre-heater and condenser: This device is an energy exchanger between feed water and purified water. Re-heater is a device that is used to absorb heat from the cooler side whereas a condenser works vice versa. Electrical energy storage (battery): During fast desalination at night time or the cloudy condition and to balance energy supply from incoming solar radiation due to cloudiness in the day time, it needs an electrical energy accumulator called a battery. This research used to model 4 numbers of batteries with a capacity of 1000mAh. Insulation system: Heat always flows by its nature by temperature difference. All sides need an insulation system to reduce the energy dissipation from the collector plate (absorber). This mechanism helps to flow the energy to the water using convection and radiation from the absorber. Sand with semi-membrane: washed and three different sand sizes arranged at different depth helps to increase the quality of the delivery water. Sand filtration can puts in vertical and horizontal positions with an arrangement from coarse to fine size sand.

Additionally, a semi-permeable membrane was added to this system at three locations as a different sand size separator and filtration system and use as a forward osmosis filtration mechanism. PV arrays: Energy collection using solar thermal collectors may slow and not consistent. This problem can tackle using a photovoltaic system with electrical energy storage called a battery. Resister: it is an energy converter. Electrical energy converts to heat energy and its energy amount vary based on its current variation. Glass: The incoming solar energy pass through 30 degrees tilted transparent glass; and this glass also has an application by holding the thermal energy of the system. And the efficiency of 30-degree solar still is better than 15 and 45-degree (Manoj Dubey, Dhananjay R. Mishra 2019). Glass cover is preferable in conventional solar stills desalination since it has a high transmittance for solar energy, opaque to thermal radiation, resistance to abrasion, high wettability, high stability, and its universal availability. Corrugated solar still: is a mechanism applied to increase the energy-absorbing and transfer ratio by increasing the contact area of an absorber plate and water. The total area increased by Corrugated was 0.2835 m^2 around and it covers around 30 percent of the total area.

2.2 Materials used for Experimentation

The water was collected from bonds and lakes from Aksum around the university, and the experimentation was done engineering at the thermo-fluid laboratory. Chemical and biological analysis of feed water, pre-treated, and purified water were carried out at department geology at Mekele University. And during the experimental and post-experimental, many types of equipment used to facilitate the research work reliable. During experimentation (Like mass balance, thermocouple, infrared thermometer, and computer) and post experimentation (during water chemistry analysis like Hanna pH meter, Vernier Lab, and nephelometer or turbidimeter device) was used.

2.3 Water Treatment Mechanism

First, the feed (un-purified) water is filtered out at the Sand and semi-membrane filtration mechanism to remove particles and semi-solid materials. Sand filtration and forward osmosis using semi-membrane was used as pre-purification for fast filtration and can be used alone as a water purification mechanism using slow sand filtration. After the particle removes, the feed water goes to the pre-heater to increase energy and ready to escape the molecules of water from the surface of the water called evaporation.

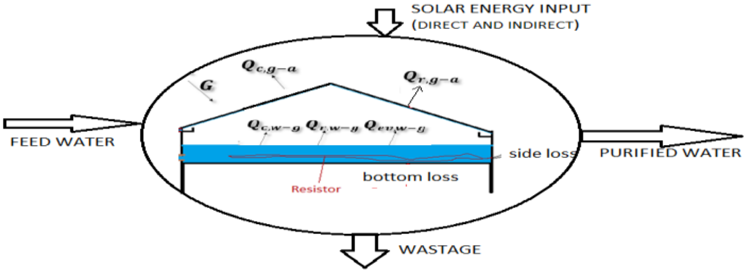


Fig.2: Schematic drawing for the use of hybrid water production mechanism

After it heats up, the water enters the absorber (heat collector plate). This collector absorbs solar radiation comes from the sun pass through the glass, and it is converted to thermal energy.

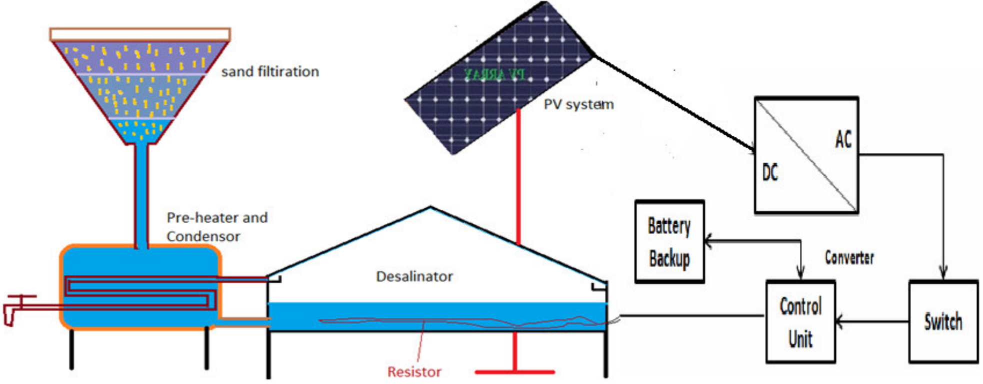


Fig. 3: Schematic diagram of the proposed water purification system

This thermal energy is transferred to the water via convection and radiation. Heat gained water molecules evaporated. And the evaporated water was condensed at the inner part of the glass and run down along the glass cover due to gravity to the purified water collector (or beaker). At the fast desalination mechanism, some vapours may go through the nozzle without touching the glass cover and condensed within the condenser.

2.4 Sand filtration

Sand filtration water purification is classified as fast sand filtration and slow sand filtration. It filters multiple cleaning mechanisms including mechanical filtration and sedimentation. It also filters biological where an ecosystem develops microbial used as biofilm; and it contributes to the cleaning process (S. Chan et al. (2018).

2.4.1 Slow sand filtration(SSF)

SSF has been used for drinkable water production for a hundred years and above (S. Chan et al 2018). It is the easiest way of water purification and used to purify water by removing pathons, particles, denitrification, chemical and biological (like bacteria) (Langenbach, K., et al. 2009, Ijadunola, J.A., et.al 2011, Bauer, R., et al. 2011, Aslan, S. & Cakici, H. 2007). SSF is used to filter out/ remove different microbial contaminants like viral pathogens, Escherichia coli, Cryptosporidium spp., Clostridium spp. and toxins (Bourne, D.G. et al 2006, Elliott, M.A., et al 2008, Hijnen, W.A. et al 2007). In developing countries, this is the most feasible form of water purification for remote rural areas (Timoteo B. Bagundol et al 2013).

(a) (b)

Fig. 4: (a) Slow and fast sand filtration (b) hybrid water purification

2.4.2 Fast sand filtration (FSF)

This type of mechanism is mostly used for pre-purification. Desalination and reverse osmosis need pre-purification to minimize the load of the purification process. Except for E.coli and bacteria, turbidity, and water cloudiness can reach the WHO standard (Yogafanny Ekha, Fuchs Stephan, ObstUrsula 2014). Disinfection of all bacteria can be completely reduced by adding chlorine per the standard.

2.5 Solar still Desalination

Desalination is a process that separates and purifies the feed water (like saline water, seawater, and brackish water) to draw water. Desalination can be categorized as separation (or filtration) and evaporation-condensation (V.G. Gude 2018). An evaporation-condensation process needs thermal energy for freshwater production. And this process needs various forms of energy with including other parameters. Solar still desalination one of the energies intensive water purifications, while the desalination process is simple, low cost, low running cost, and feasible for remote areas. According to the form of solar energy uses, solar still desalination can be categorized into slow and fast desalination.

2.5.1 Slow solar still desalination

Slow desalination is natural desalination without adding external renewable energy except for the natural incoming radiation from the sun and this process is called passive desalination process.

2.5.2 Fast solar-powered desalination

This process is a forced (or active) desalination method and it uses integrated renewable energy sources like biomass, bio-fuel, and electricity (M.A. Al-Nimr, W.A. Al-Ammari 2016).

Fig. 5: solar water purification with sand filtration pre-treatment and solar electric resistor

Developed countries and western nations prefer reverse osmosis (RO) systems since they use electric power efficiently, while the Gulf countries and the Middle East prefer multi-stage flashing (MSF) and Multistage desalination (MED) systems since they have abundant oil sources (Ahmed Alkaisi et al 2017). In developing countries like Africa, Solar powered solar desalination is more preferable since solar irradiation is the most abundant source of energy. Fast solar-powered desalination uses the combination of the main solar desalination categories (direct and indirect).

2.6 Heat Transfer Analysis

Heat can be lost in three directions of the water purification system. Bottom, lateral and top directions of the system in which energy dissipates to the environment (or surrounding).

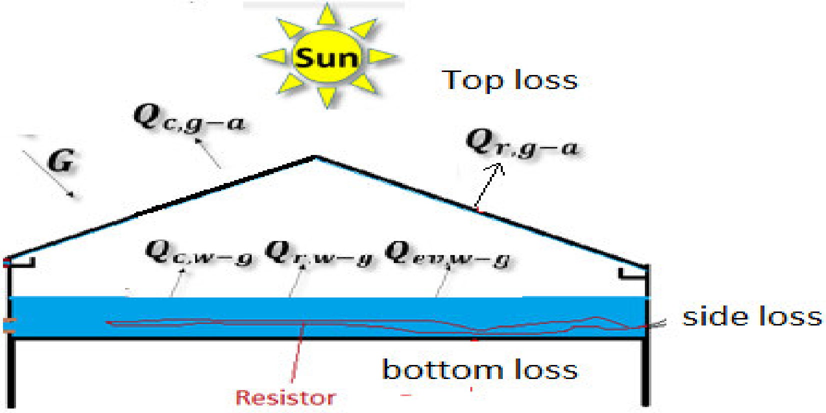


Fig. 6: Overall heat flow directions

The purification mechanism uses all three fundamental heat transfer modes; convection, conduction, radiation, and various combinations. Incoming solar radiation (G) is called insolation absorbed by the absorber and it transfers to the water by convection and the bottom by conduction. From the surface of the water to the glass, heat energy is transferred by convection and evaporation. Finally, energy dissipated from the system through the insulation and glass (bottom and sides) via convection and radiation (Fig. 6).

2.6.1 Mathematical Modelling

To simplify the overall energy analysis, some assumption has to be listed as follows (M. Al-harahsheh et al. 2018):

- Negligible heat capacity of insulating materials and glass
- Water and air behave as an ideal glass
- No pressure drop due to friction and air leakage
- And the steady-state and steady flow process

A steady flow steady-state conditions, the energy equation of any solar thermal collector is as follows:

$$\dot{Q}_{solar,useful} = A_aG_a - \dot{E}_{opt,loss} - \dot{q}_{lost} \tag{3.1}$$

Where, $\dot{Q}_{solar,useful}$=Useful heat energy gained by the solar collector; A_aG_a=Incoming solar energy to the collector; $\dot{E}_{opt,loss}$=Solar Energy loss due to the optical collector; $\dot{q}_{lost}$=Thermal Energy losses.

And the energy balance due to resistor supplied by off-grid or grid power system

$$\dot{Q}_{PV,useful} = P_{PV,supplied} - \dot{q}_{lost} \tag{3.2}$$

Where, $\dot{Q}_{PV,useful}$ = Useful solar heat produced by the resistor; $P_{pv,supplied}$=Solar Energy supply by the PV system;

Overall heat transfer study of the whole system was analysed based on First law thermodynamics analysis for the integrated mechanism.

$$\dot{Q}_{SE,useful} = A_aG_a + P_{PV,supplied} - \dot{E}_{opt,loss} - \dot{Q}_{lost} \tag{3.3}$$

Where, $\dot{Q}_{SE,useful}$ =Total useful heat energy produced by the integrated solar collector; $\dot{Q}_{lost}$ = Total thermal Energy losses

To simplify the energy balance within the integrated device categorized into four most essential sub-systems (like glass, collector, water and heat exchanger)

I. Water

The energy balance at the element of the un-purified water is given by (Zurigat, Y.H., Abu-Arabi, M.K. 2004, Moh'd A. Al-Nimr, Wahib A. Al-Ammari 2016)

$$q_{I,w} + q_{c,p-w} + q_{in} + E_{gen} = q_{c,w-g} + q_{r,w-g} + q_{evap} + q_{out} + \Delta E \tag{3.4}$$

Where, Heat energy transfer by radiation to the water film

$$q_{I,w} = IA\,\tau_g\,\alpha_w \tag{3.5a}$$

Convection heat transfer from the absorber to the water part

$$q_{c,p-w} = Ah_{c,p-w}(T_p - T_w) \tag{3.5b}$$

Heat energy at the water part is determined by:

$$q_{in} = \dot{m}_w C_{PW} T_w \tag{3.5c}$$

Heat energy transfer by radiation from water to the glass:

$$q_{c,w-g} = Ah_{r,w-g}(T_w - T_g) \tag{3.5d}$$

Radiation heat flow from water to the glass cover

$$q_{r,w-g} = Ah_{r,w-g}(T_w - T_g) \tag{3.5e}$$

Evaporation heat flow from un-purified water to the glass:

$$q_{evap} = Ah_{evap}(T_w - T_g) \tag{3.5f}$$

Heat energy out from water part:

$$q_{out} = (\dot{m}_w - \dot{m}_c)C_{PW}T_{w,o} \tag{3.5g}$$

II. Glass

Total energy absorbed with the glass is:

$$E_g = \rho_g C_p V_g \Delta T_g \tag{3.6}$$

And energy transfer of the control glass using 1st law of thermodynamics described as follows:

$$q_{I,g} + q_{c,w-g} + q_{r,w-g} + q_{evap} = q_{c,g-a} + q_{r,g-a} \tag{3.7}$$

Where, Heat flow by radiation to the glass from the air is (Moh'd A. Al-Nimr, Wahib A. Al-Ammari 2016):

$$q_{I,g} = IA(1 - \beta_g)\alpha_g \tag{3.8a}$$

Heat energy flow by convection from the water to the glass cover is (Zurigat, Y.H., Abu-Arabi, M.K. 2004):

$$q_{c,w-g} = Ah_{c,w-g}((T_w - T_g) \tag{3.8b}$$

The heat flow coefficient due to convention among glass and water is analyzed by (Sampathkumar, K.T et al 2010):

$$h_{c,w-g} = 0.884[(T_w - T_g] + \left(\frac{P_w - P_g}{268.9*10^3 - P_w}\right)T_w]^{1/3} \tag{3.8c}$$

$$P_w = \exp[23.317 - (\frac{5144}{273 + T_w})] \tag{3.8d}$$

$$P_g = \exp[23.317 - (\frac{5144}{273 + T_g})] \tag{3.8e}$$

Heat energy transfer due to radiation to the glass cover from the water is (Sampathkumar, K.T et al 2010, Moh'd A. Al-Nimr 1, Wahib A. Al-Ammari 2016]:

$$q_{r,w-g} = Ah_{r,w-g}((T_w - T_g) \tag{3.8f}$$

The heat transfer coefficient by radiation amongst water and glass is analyzed by (Incropera, F.P.Det al 2011):

$$h_{r,w-g} = 0.9\,\sigma(T_w - T_g) \tag{3.8g}$$

Heat flow due to evaporation from the water part to the glass is analyzed by (Zurigat, Y.H., Abu-Arabi, M.K. 2004):

$$q_{evap} = Ah_{evap}(Tw - Tg) \tag{3.8h}$$

The coefficient of evaporative heat flow is described by (Kumar, S., Tiwari, G.N.1996):

$$h_{evap} = 16.27 * 10^{-3} * h_{c,w-g}\left(\frac{P_w - P_g}{T_w - T_g}\right) \tag{3.8i}$$

Heat flow by convection method from the glass to the environment is (Zurigat, Y.H., Abu-Arabi, M.K. 2004):

$$q_{c,g-a} = Ah_{c,g-a}(Tg - Ta) \tag{3.8j}$$

And, the coefficient of convective heat transfer is given by (Zurigat, Y.H., Abu-Arabi, M.K. 2004):

$$h_{c,g-a} = 2.8 + 3V \tag{3.8k}$$

Heat flow by radiation to the environment from glass cover is: (Munzer S. Y. Ebaid, and Handri Ammari 2015):

$$q_{r,g-a} = Ah_{r,g-a}(Tg - Tsky) \tag{3.8l}$$

The sky temperature is described by (Akhtar, N., Mullick, S.C. 2007):

$$T_{sky} = 0.552x(Ta + 273)^{\frac{3}{2}} - 273 \tag{3.8m}$$

III. Heat absorber (or Collector)

An energy equation balance of the absorber plate is given by (Munzer S. Y. Ebaid, and Handri Ammari 2015):

$$q_{I,p} = q_{c,p-w} + q_{p,loss} + \Delta e_p \tag{3.9}$$

Where Heat flow due to radiation to the absorber plate is:

$$q_{I,p} = IA\,\tau_g\,\tau_w\,\alpha_p \tag{3.10a}$$

Heat flow by convection from absorber plate to water:

$$Qc_{,p-w} = Ah_{c,p-w}(T_p - T_w) \tag{3.10b}$$

Heat energy loss from the collector plate:

$$Qp_{,\,loss} = Q_{p,bottom} + Qp_{,\,side} \tag{3.10c}$$

Heat energy loss from the bottom of the absorber to air:

$$Q_{P,\text{ bottom}} = A(T_p - T_a)/ R_{b,\text{ total}} \tag{3.11d}$$

Similarly, heat loss from the side of the absorber to the air:

$$Q_{p,\text{ side}} = A(T_p - T_a)/ R_{b,\text{ total}} \tag{3.11e}$$

The overall energy dissipation is given by:

$$R_{b,total} = R_{b,insulation} + R_{b,casing} + R_{b,convection} \tag{3.12}$$

or

$$R_{b,total} == \frac{X_w}{K_w A} + \frac{X_{ch}}{K_{ch} A} + \frac{X_s}{K_s A} \tag{3.13}$$

The overall energy stored within the absorber and insulation system is:

$$E_{p\&i} = \rho_p C_p V_p \Delta T_p + \rho_i C_i V_i \Delta T_i \tag{3.14}$$

2.7 Mass balance

The amount of purified water (condensation rate) by the hybrid solar energy water purification mechanism is described by (Moh'd A. Al-Nimr, Wahib A. Al-Ammari 2016, Kumar, S., Tiwari, G.N. 1996, Kumar, S., Tiwari, G.N. 1996, Munzer S. Y. Ebaid, and Handri Ammari 2015, Akhtar, N., Mullick, S.C. 2007) and Q_{evap} of the integrated and desalination alone were 16.79 and 4.3175 MJ per day.

$$\dot{m} = \frac{Q_{evap}}{h_{fg}} \tag{3.15}$$

2.8 The efficiency of the system

The performance of the integrated solar still analyzed based on the ratio of useful energy and energy input described by (Moh'd A. Al-Nimr, Wahib A. Al-Ammari 2016):

$$\eta_{system} = \eta_{still} \eta_{PV} \tag{3.16}$$

Where, efficiency Integrated solar desalination is described by (Munzer S. Y. Ebaid, and Handri Ammari 2015):

$$\eta_{still} = \frac{\dot{Q}_{evap}}{IA + P_{pv}} \tag{3.17a}$$

Power production by the PV system is given by:

$$P_{pv} = \eta_{pv} IA \tag{3.17b}$$

The performance of the PV system is described by (Dubey, S., Tay, A.A.O.2013):

$$\eta_{pv} = \eta_{T,ref}(1 - \beta_{ref})(T_{pv} - T_{ref}) \tag{3.17c}$$

Where, the coefficients of $\eta_{T,ref}, \beta_{ref}$ and $T_{ref})$ are taken for a Mono-Si PV cell

2.9 Resistance Heating System

The resistance to the current flow generates heat in the Ni-Cr coil, and heat flow to the fluid system via convection and conduction. The mathematical power dissipated in an electric resistance wire can be stated using ohmic heating; occurs when a resistor is heated as current flows through it.

$$P = IR^2 \tag{3.18}$$

Where; P = Power (in Watts), R= Resistance (in Ohms), and I = Current (in amps)
The resistance of the coil is given by:

$$R = \frac{\rho}{A} L \tag{3.19}$$

Where; L= Electrical wire length, A= cross-sectional area, and ρ= resistivity
The specific resistivity of conductor's changes with temperature with limited temperature range; it has linear approximation:

$$\rho(T) = \rho(T_0)\,(1 + \alpha\,(T - T_0)) \tag{3.20}$$

Were, α - the coefficient of temperature, T0- ambient temperature, ρ (T0) - the electrical resistivity at ambient temperature, ρ (T) - the resistivity at a given temperature

2.10 Heat exchanger

There are three heat energy flow mechanisms to be defined on the solar desalination heat exchanger (pre-heater and condenser):

1. Convective heat energy flows from condensed water to the inner surface part of the tube,
2. Conductive heat energy flow through the tube wall,
3. And, Convective heat energy flow from the outer surface of the tube wall to the preheated water (outside fluid).

And the heat energy flow rate per unit length is described by:

$$\dot{Q} = \frac{2\pi k(T_A - T_B)}{\frac{k_1}{r_1 h_1} + \frac{k_2}{r_2 h_2} + \ln\left(\frac{r_2}{r_1}\right)} \tag{3.21}$$

Or

$$\dot{Q} = 2\pi r_2 h_0 (T_A - T_B) \tag{3.22}$$

Where ho=is the convective heat transfer coefficient, TA: the bulk temperature of the fluid TB: interior wall temperature, r_2 = radius of the external surface.
The overall heat transfer coefficient, ho, is:

$$\frac{1}{h_0} = \frac{r_2}{r_1 h_1} + \frac{r_2}{k_2}\ln\left(\frac{r_2}{r_1}\right) + \frac{1}{h_2} \tag{3.23}$$

2.11 PV system modeling

The PV system used in the hybrid water purification system is to increase water productivity rate by adding heat energy when the current pass through the electrical resistor. The PV cell photocurrent which depends on radiation and temperature is described by (Bellia H, Youcef R, Fatima M. A 2014, Bellia H, Youcef R, Fatima M. A 2014, Pandiarajan N, Muthu R. 2011):

$$I_{ph} = [I_{sc} + K_i(T - 298)]\frac{\beta}{1000} \tag{3.24}$$

And, current generated using solar PV module can be approximated by:

$$I_{PV} = N_p * I_{ph} - N_p * I_o\left[\exp\left\{\frac{q*(V_{ph} + IphR_s}{NsAKT}\right\} - 1\right] \tag{3.25}$$

Where I_{pv} is the PV module current, V_{pv} is the voltage, I_{ph} is the photo generated current, Ns - is the number of cells in series, N_p - is the number of cells in parallel, n -is an idealist factor of the diode, IRS - is a reverse saturation current, and AkT is the thermal voltage. Practically, only about 35% of the total solar irradiance is converted to electrical power. And the output power from the PV modules can be determined using the equation:

$$P_{OPV} = I_{OPV} * V_{OPV} \tag{3.26}$$

Where P_{OPV} –photovoltaic power output and V_{OPV} –photovoltaic voltage output

2.12 Economic Analysis

The cost analysis of one project is a crucial thing for achieving an economically feasible water purification technology. Based on researchers, the economic analysis includes like first annual cost, first annual salvage value, annual maintenance cost, and total annual cost (K. R. Ranjan and S. C. Kaushik 2016, Ali Heydari and Nader Rahbar 2017, Kabeel, A.E., Hamed, A.M., & El-Agouz, S.A. 2010, Kianifar, A., Zeinali Heris, S., Mahian, O. 2012).
The first annual cost (FAC) of the system is described by:

$$FAC = p\frac{i(1+i)^n}{(1+i)^n - 1} \tag{3.27}$$

Where p is the capital cost of the system, I: the interest rate (12%) of banking facilities, and n is the working life of the system (10 years).
The salvage value would be evaluated by 20% of the total cost (Shiv Lal *et al*. 2013, A.O Ahmed, M.H Onsa and H.M Elsaki 2014, Abderrahmane Abenea, Ahmed Rahmani, Zoubir Zahzouh, 2017] and the first annual salvage value (ASV) of the product can be analyzed by:

$$ASV = 0.2p\frac{i}{(i+1)^n - 1} \tag{3.28}$$

Total annual cost (ATC) can be determined by:

$$ATC = FAC + AMC - ASV \tag{3.29}$$

Annual maintenance cost (AMC) is considered as 15% of FAC (K. R. Ranjan and S. C. Kaushik 2016):
The cost of 1.0 liter of purified water is estimated by dividing annual cost by the still annual yield the system (Abderrahmane Abenea, Ahmed Rahmani, Zoubir Zahzouh, 2017). Water production cost per litter can be determined by:

$$CPL = \frac{ATC}{M} \tag{3.30}$$

Where M is the average annual productivity
The discounted payback period (N_{dp}) is described by (A.O Ahmed, M.H Onsa, and H.M Elsaki 2014):

$$N_{DP} = \frac{\ln(B-C) - \ln[(B-C) - iC_0]}{\ln(1+i)} \tag{3.31}$$

Where, i = interest rate, Co = initial capital investment, B = benefits of the project=CF = Yearly water production (Myearly) * specific price (Sp); C=ATC=Costs of the project

3. RESULT AND DISCUSSION

The experimental set-up was designed and installed at the thermo-fluid Laboratory, Department of Mechanical Engineering, Aksum University. Aksum has dry weather and a short rainy season with an almost clear sky and its solar radiation is a minimum of 5.46 kWh/m2 per day and a maximum of 6.82 kWh/m2/day in August and April respectively, with an average of 6.09 kWh/m2/day. The behavior of higher solar intensity brings higher temperatures. So, as solar radiation increases the overall efficiency increases, and at the same time, power production from the PV system and solar still increases (Moh'd A. Al-Nimr, Wahib A. Al-Ammari 2016). And by integrating conventional solar still with a PV system, overall water production and efficiency were increased as solar irradiances increased. The experiment was started from 7:00 am up to 6:00 pm within three consequent days for conventional and integrated solar still water purification devices separately. Experimental results were presented and discussed in tables and graphical methods to show the difference between the two different energy sources use water purification mechanisms (section 3.1).

3.1 Water production rate

Experimental measurement was done using direct solar energy with/without indirect solar energy. The cost of an integrated system is more costly than the conventional one though the water productivity is incomparable with solar still using direct solar.

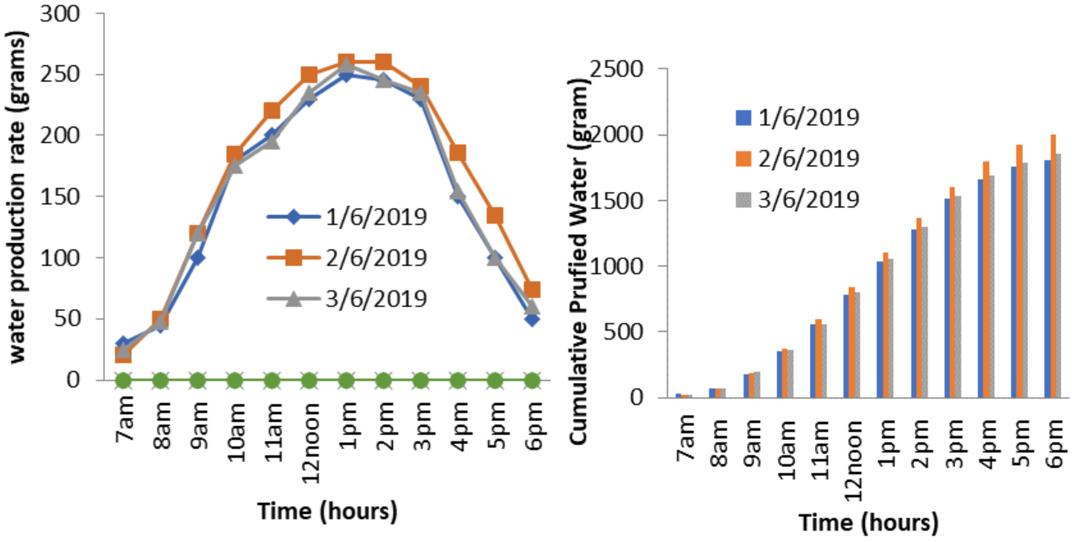
Table 1: Total daily distillate collected without PV system

Day	Feed water amount	Av. solar radiation (kw-hr/m^2)	Min. temp. (^{0}C)	Av. Temp. (^{0}C)	Max. Temp. (^{0}C)	Wind speed 10m (m/s)	Daily total distillate (ml)
01/06/19	3L	6.00	20.12	25.94	33.06	2.97	1800
02/06/19	3L	6.82	18.73	25.41	31.64	3.62	2000
03/06/19	3L	6.01	19.65	26.25	33.52	3.22	1850

Table 2: Total daily distillate collected with PV system

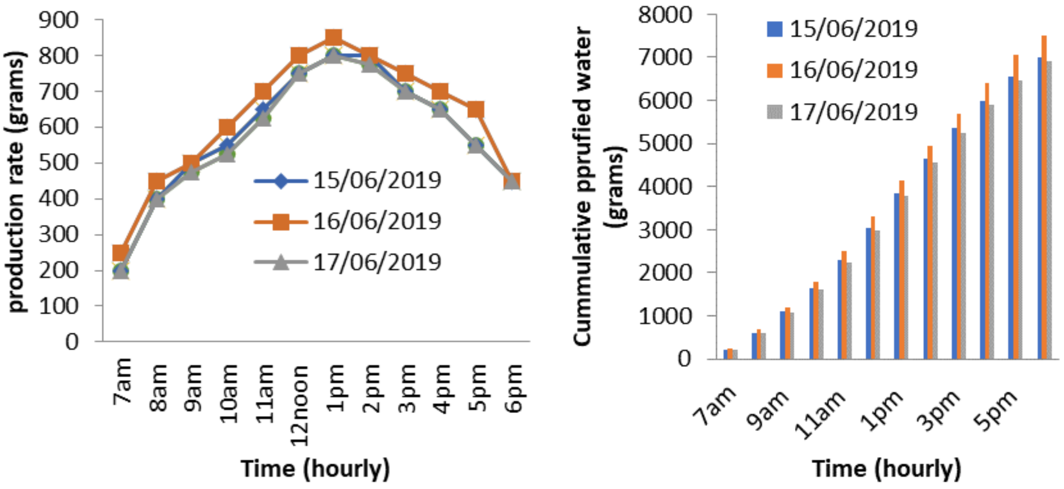
Day	Feed water amount	Av. solar radiation (kw-hr/m^2)	Min. temp. (^{0}C)	Average Temp. (^{0}C)	Max. Temp. (^{0}C)	Wind speed (m/s)	Daily total distillate (ml)
15/06/19	10L	6.92	18.76	23.04	28.97	3.26	7000
16/06/19	10L	7.00	18.91	23.70	29.42	2.47	7500
17/06/19	10	6.64	18.95	22.85	28.73	3.27	6900

The variation of total hourly distillate output of different water masses has been plotted for solar still desalination with/without the PV system (Fig.7&8). Based on experimental results, the amount of total cumulative distilled water from conventional solar still and integrated solar still was around 1.8L and 7 L respectively.



(a) *(b))*

Figure 7: purified water without PV system (a) Hourly distillate collected (b) Hourly cumulative



(a) *(b))*

Figure 8: Integrated solar energy (a) hourly distillate collected (b) hourly cumulative purified water

Solar-powered desalination was a reliable, simple, and feasible process in which saline (or un-purified) feedwater converts to fresh draw water with simple, low cost and economical technology; and thus it was suitable for rural areas where the level of income is relatively very low (Selvi S. R. et al. 2014). Solar-powered desalination was categorized as direct and indirect. And these solar energy use water purification technologies were tested its productivity (Fig. 7-8), performance (Table-2), and economical comparison. The direct method was a simple solar still and heat absorption takes place at the same device whereas indirect solar-powered desalination was like a plant and it used two subsystems, a solar collector (or PV system) and a solar still desalination unit.

3.2 Performance analysis

Several parameters affected the performance of the conventional solar still (passive or active). Generally, these parameters classified as uncontrollable (such as ambient temperature, the intensity of solar radiation, and wind velocity) and controllable (such as glass cover angle, depth of water, materials, and glass cover thickness) (M.A. Al-Nimr, W.A. Al-Ammari 2016, Prakash, P., Velmurugan, V. 2015). The overall efficiency of the conventional solar still and IPVSSWP was 26.65 % and 29.61 % respectively. And by replacing the power input of the photovoltaic power supply by the grid power supply, the efficiency of integrated grid power and solar still water purification (IGSSWP) was 50.26%. The amount of useful energy absorbed by evaporated water was around 16.79 and 4.32 MJ for the integrated and conventional solar desalination respectively. Energy loss and useful energy of integrated photovoltaic solar still water purification (IPSSWP) and integrated grid power solar water purification (IGPSSWP) were the same. And the efficiency difference among the two was due to the efficiency of the PV system is too small relative to the efficiency of grid power.

3.3 Water chemistry

TDS level of any water may vary based on the concentration of calcium, hydrogen carbonate, sodium, magnesium, potassium and carbonate, sulfate, chloride, and nitrate anions. And it varies from the excellent level up to unacceptable as the concentration increases. Excellent, if it less than 300 mg/l; good, if it varies from 300 to 600 mg/l; fair if it varies from 600 to 900 mg/l; poor, from 900 to 1200 mg/l; and unacceptable, if it is greater than 1200 mg/l (Bruvold WH, Ongerth HJ. 1969). From the experimental result, the TDS value dramatically decreased from good results (689.67 TDS) of the feed water to the excellent result (48.48 TDS) of the purified water (Table 3).

Table 3: Water chemistry of feed water, pre-purification water, and the purified water

Water Chemistry	Water Type		
	Feed water	Pre-treated water	purified water
TDS	689.67	676.74	48.48
Turbidity	1.89NTU	1.57NTU	0.02NTU
PH	7.91	7.52	6.95
Electrical conductivity	967	947	68.5
Total hardness	124.3 mg/l	121.47 mg/l	7.0625 mg/l
True colour	7.68TCU	6.54TCU	0.62TCU

The turbidity of the untreated feed water was cloudy and no clear due to silts and clays from shoreline erosion, and other bottom organic sediments and re-suspended materials. The measurement of turbidity for the feed water is not equivalent to raw material to protect the nephelometer or turbidimeter device. The PH values of samples (after and before treated) are similar and within the drinking water standards (6.5-8.5) based on WHO, SASO, GCS, EEC, and CGL standards. And electrical conductivity is the total dissolved salts, solids, and ions and directly proportional to each other. The experimental result shows, electrical conductivity of feed water and freshwater were 967 and 68.5 respectively. The concentrations of hydrogen ions are almost similar for feed water pre-treated water and the absolute purified water. During the experiment, the purified water acidity slightly increase due to the black paint within the absorber. Total hardness is the amount of dissolved calcium and magnesium (Alam et al. 2017) of feed water, pre-purification water, and purified water is 124.3 mg/l, 121.475 mg/l, and 7.0625 mg/l respectively. Based on the general guidelines, classification of waters are: 0 to 60 mg/L as calcium carbonate and magnesium is classified as soft; moderately hard from 61 to 120 mg/L; hard from 121 to 180 mg/L as; and very hard if it is more than 180 mg/L (Alam et al., 2017). Therefore, feed water and pre-purification water classified under moderately hard whereas the purified water is classified under soft water.

3.4 Economic Analysis

Cost analysis usually aims to assess the cost of a litter or a cubic meter of drinkable water and estimates the contribution of each item cost to the total cost (M.A. Eltawil et al., 2009). And the cost of one litter purified water of the conventional solar still integrated solar-powered desalination, for five year lifetime, was around 2.5 and 1.5 ETB respectively.

3.4.1 Economic feasibility

The economic feasibility of water purification is the comparisons of productivity with its production cost. Integrated solar desalination is economically feasible for rural applications in remote African countries. It is the most simple and carbon-free technology. So, the technology does not only reduce the GHG emissions (Shiv Lal *et al*., 2013), but also help in energy conservation and preventing diseases. And the average CO2 equivalent for electricity may be assumed to 0.98 kg/kWh CO_2 (K. R. Ranjan and S. C. Kaushik 2016). Generally, the application of solar use water purification may categorize as tangible and non-tangible. By considering the annual maintenance cost of the manufactured material was 15 % of the total cost, the payback period of conventional solar still and hybrid (integrated) water purification is 1.274 and 0.61 respectively, and the unit water purification cost was US $ 329.50 and the US $ 674.50 respectively (Table 5).

4. CONCLUION

In this research paper, an integrated PV system and solar thermal energy were suggested to increase the productivity rate of water. The objective of the paper was to design and propose eco-friendly water purification technology for the remote rural area of Tigray with high production and efficiency. The corrugated solar absorber was used to increase the overall efficiency of the system by increasing the overall area of 0.2835 m^2 and it covers around 30 percent of the total area. Based on the thermodynamic analysis, a steady-state mathematical model has been developed to study the overall performance of the system. And the overall efficiency of conventional solar still an integrated PV and solar power energy use water purification was 26.65 % and 29.61 % respectively. And by replacing the PV energy input the grid power, the efficiency of IGPSSWP was around 50.26%. The payback period of conventional solar still and hybrid (integrated) water purification is 1.274 and 0.61 respectively, and the unit water purification cost was US $ 329.50 and the US $ 674.50 respectively. Finally, the governmental and non-governmental organizations should have supply low-cost PV panels for the low-income local community, since it is a high cost during the initial investment.

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