International Journal of Latest Engineering and Management Research (IJLEMR)
ISSN: 2455-4847
www.ijlemr.com || Volume 04 - Issue 02 || February 2019 || PP. 55-62

Design and Optimization for a Solar Water Heating System by Cost Minimization: A case study of a Student Hostel in the East African School of Aviation, Kenya

Leonard K Rotich[1], Jared H. Ndeda[2], Joseph N. Kamau[3].
[1] *Institute for Energy & Environmental Technology, Jomo Kenyatta University of Agriculture & Technology, Nairobi, Kenya*
[2] *Department of Physics, Jomo Kenyatta University of Agriculture & Technology, Nairobi, Kenya*
[3] *Department of Physics, Jomo Kenyatta University of Agriculture & Technology, Nairobi, Kenya*

Abstract: Hot water demand in densely populated buildings accounts for a significant fraction of total energy consumption over a given period of time. Solar Water heating system can be used as an alternative energy source to meet hot water demand instead of electricity or fossil fuels. In this study, a Solar Water Heating System (SWHS) was designed to meet the hot water demand of a students' hostel with a bed capacity of 303. Hourly Solar radiation and consumption data were used to simulate system performance. The proposed SWH System was composed of 22 centrally placed flat plate collectors and storage with a cumulative capacity of 6600 Liters. The Cost of Energy for the system was found to be KSh6.45/kWh which is favourable when compared with the prevailing grid energy cost of Ksh 18/kWh.
Keywords: Excel,Solar water heating, Simulation, Solar radiation, Cost of Energy.

1.0 Introduction

Solar thermal technology uses sun's energy to generate thermal energy with minimal emissions. This thermal energy is used to heat water, other fluids and solid storage materials which are used as medium of transferring the same energy. Thermal heat from the sun can be stored in the form of Sensible Heat (SH) or Latent Heat (LH) depending on the properties of a chosen storage material [1]. Water is a good material for storing heat in the form of SH because of its high specific heat capacity and availability [1]. Solar water heating therefore provides a means for harnessing sun's heat energy for various applications such as industrial heating, space heating and domestic hot water demand.

1.1 Solar Thermal Energy Modelling

Different technologies are available for harvesting the sun's heat energy but all utilize the same principle, to employ a collector, heat exchanger, heat transfer medium, heat storage system and a monitoring system. Solar collectors have radiation absorbing surfaces or plates. The radiant flux striking a plate is given byequation (1) [2].

$$P_{Rad} = \tau_{cov} A_P G \tag{1}$$

Where;G is the irradiance on the collector, $A_P$is the exposed area on the plate and $\tau_{cov}$is the transmittance of the glazing. Only a fraction α_p of this flux is absorbed. The heated plate is hotter than the environment hence it loses heat at a ratedescribed by equation (2) [2].

$$P_L = \frac{(T_p - T_a)}{R_L} \tag{2}$$

where; R_L is the resistance to heat loss from the plate at temperature T_P to the environment at temperature T_a
The net heat flow in the plate is given by the difference of equations (1)and (2) as shown in equation (3) [2].

$$P_{net} = A_P\,[\tau_{cov}\alpha_P G - U_L(T_P - T_a)] \tag{3}$$

Where $U_L$is the overall heat loss coefficient given by; $\frac{1}{A_p R_L}$

Equation (3)is referred to as Hottel-Whillier-Bliss equation which illustrates the parameters that influence performance of a collector. One set of the parameters is related to the transmission and absorption of heat while the other set is related to retention and movement of heat [2].
In order to select a suitable water heating system, hot water demand at a site is estimated based on the type of consumer, inlet water temperature, outlet water temperature as well as the quantity of water required in liters(L). Quantity of hot water demanded can be reasonably determined by estimating the number of users and appliances

in most dominant functional room in a standardized building [3]. It is desired that water temperature in the storage tank be at a minimum of 60°C to prevent growth and multiplication of harmful *legionella* bacteria in the system [4]. If hot water is utilized at a temperature other than 60°C, adjustment is made to demand at 60°C. Equation (4) is used to adjust and relate demand at another temperature to demand at 60°C.

$$D_{(T)} = D_{(60)} \frac{T - T_i}{(60 - T_i)} \tag{4}$$

Where; T is desired water temperature, T_i is the inlet water temperature.
Total energy required per day to meet hot water demand is given by equation (5).

$$L = V\rho c\left(T_{(60)} - T_i\right) \tag{5}$$

Where; V is volume of water, ρ is density of water and c is the specific heat capacity of water.
A Solar Water Heating system collector area must be determined in order to select a size that can meet the desired demand. Total energy harnessed by a collector is directly proportional to the area exposed to the sun's radiation. For sheltered collectors such as the flat plate collectors, thermal heat capture is related to its material properties such as transmittance, absorptivity and resistance to heat loss. Equation (6) gives a simplified relationship between irradiance and the collector area size.

$$A_C = \frac{L}{\eta_{solar} \cdot I_{av}} \tag{6}$$

Where; A_C is the collector area, η_{solar} is the collector efficiency and I_{av} is the average daily insolation.

1.2 Solar Resource Potential Representation

Solar radiation available over a given location varies from hour to hour depending on the sun's position at different times of the day and the amount of cloud cover. In order to predict a Solar system energy output during design stage, it is preferable to estimate hourly production using available solar radiation data. However, if only the monthly mean daily irradiance data is available, hourly mean irradiance should be estimated [5]. There are empirical models that have been developed for estimating hourly Solar Irradiance from available monthly mean daily irradiance data. Equations(7) and(8) show a model for estimating extraterrestrial horizontal radiation according to [5].

$$G_{on} = G_{sc}(1 + 0.033\left(\cos\frac{360n}{365}\right) \tag{7}$$

$$\bar{G}_o = \frac{12}{\pi} G_{on}\left[\cos\phi\cos\delta\left(\sin\omega_2 - \sin\omega_1\right) + \frac{\pi(\omega_2 - \omega_1)}{180°}\sin\phi\sin\delta\right] \tag{8}$$

Where:
G_{sc} = the solar constant (1.367 kW/m2)
$\bar{G}_o$ = the extraterrestrial radiation averaged over a time step (kW/m^2)
G_{on} = the extraterrestrial normal radiation (kW/m^2)
$\phi =$ latitude angle for the location (°)
$\delta =$declination angle (°)
ω_1 = the hour angle at the beginning of the time step (°)
ω_2 = the hour angle at the end of the time step (°)
Solar resource data give the average amount of radiation striking a horizontal surface at the bottom of the atmosphere (same as the earth's surface) in each time step. The ratio of the earth's surface radiation to the extraterrestrial radiation over a given time step is called the Clearness Index (K_T) as described by equation (9)[6].

$$K_T = \frac{\bar{G}}{\bar{G}_o} \tag{9}$$

Where:
$\bar{G}$ = the global horizontal radiation over the earth's surface averaged over a time step (kW/m^2)
Solar radiation reaching the earth's surface has two components; beam and diffuse radiations. Beam radiation reaches the earth surface without scattering by the atmosphere while diffuse radiation reaches the earth's surface after its direction has been changed by the atmosphere. The total of beam and diffuse radiation is called global solar radiation which is expressed by equation(10)[5].

$$\bar{G} = \bar{G}_b + \bar{G}_d \tag{10}$$

Where:
$\bar{G}_b$ = the beam radiation (kW/m^2)
$\bar{G}_d$ = the diffuse radiation (kW/m^2)
Where solar resource data is available as global radiation and it is necessary to find either beam or diffuse components. [7] developed a model that gives diffuse radiation as a function of clearness index as shown in equation (11).

$$\frac{\bar{G}_d}{\bar{G}} = \begin{cases} 1.0 - 0.09K_T & for\ K_T \leq 0.22 \\ 0.9511 - 0.1604K_T + 4.388K_T^2 - 16.638K_T^3 + 12.336K_T^4 & for\ 0.22 < K_T \leq 0.8 \\ 0.165 & for\ K_T > 0.80 \quad \#\# \end{cases} \tag{11}$$

For purposes of designing a system that utilizes solar power, it is appropriate to determine the amount of radiation striking a tilted surface. In order to calculate the amount of radiation striking a tilted surface, it is assumed that the diffuse radiation is made up of three components; isotropic, circumsolar and horizon brightening components. Isotropic diffuse radiation comes equally from all parts of the sky while circumsolar originates from the direction of the sun and the Horizon component emanates from the horizon.

There are three other factors that are vital in estimating the amount of radiation falling on a tilted surface and they are; ratio of beam radiation on a tilted surface to beam radiation on horizontal surface as given by equation (12); anisotropy index (A_i)which is a measure of atmospheric transmittance of beam radiation (equation (13)); and horizon brightening factor (f) (equation (14)) [6].

$$R_b = \frac{\cos\theta}{\cos\theta_z} \tag{12}$$

Where θ and θ_z are the incidence and Zenith angles respectively.

$$A_i = \frac{\bar{G}_b}{\bar{G}_o} \tag{13}$$

$$f = \sqrt{\frac{\bar{G}_b}{\bar{G}}} \tag{14}$$

A model known as HDKR developed from the works of Hay, Davies, Klucher and Reindl may be used to estimate total radiation falling on a tilted surface by incorporating features of equations (8) to (14). HDKR model is shown by equation (15)[6].

$$\bar{G}_T = (\bar{G}_b + \bar{G}_d A_i)R_b + \bar{G}_d(1 - A_i)\left(\frac{1+\cos\beta}{2}\right)\left[1 + f\,sin^3\left(\frac{\beta}{2}\right)\right] + \bar{G}\rho_g\left(\frac{1-\cos\beta}{2}\right) \tag{15}$$

Where β and ρ_g are slope of the surface in degrees and ground reflectance in % respectively.

1.3 Solar Water Heating System

Some jurisdictions have mandatory requirements for facilities that consume a given amount of hot water per day to meet a minimum set fraction from solar thermal or any other renewable energy source. In a bid to meet such regulatory requirements, facility owners are compelled to install Solar Water heating systems. [8]. In Kenya, facilities with a daily hot water demand of 100 L are required to meet at least 60% of their hot water demand through solar water heating. [9]. Proper estimation of user needs must be done to avoid unnecessary system oversizing. [8]. Researchers such as [8] have established that actual daily water usage per person is between 20-40L. Standard guideline which proposes water usage quota of 60-100 L has often led to oversizing of heating systems [8].

Various approaches have been proposed for designing solar water heating systems and a suitable method is adopted bases on a design parameter which is considered significant in the operation objective of the system. [11] designed an optimal SWHS for an office building in South Korea using Genetic algorithm by focusing on equipment cost, energy cost and life cycle cost (LCC). [11] established that a trade of between equipment cost and energy cost results in an optimal design which gives the minimum LCC. [12] used numerical simulation to design a SWH for a house in the cold climate region and concluded that a multi tank system is more efficient than a single tank with thermal stratification. In this paper, numerical simulation will be used to design a SWH System for serving hot water demand of a student hostel in Kenya by using an objective function of system cost minimization.

2.0 Methodology

Solar water heating system for a hostel in a learning institution (East African School of Aviation, EASA) was designed by analyzing important parameters that affect operation of the system. Hot water demand at the facility was estimated by determining the number of beds and occupancy over an entire year. The power ratings and the number of electrical water heaters available for use in the facility were ascertained and the daily hot water demand load profile estimated. Solar resource potential at the site was freely sourced from National Aeronautical Space Authority (NASA) website (https://power.larc.nasa.gov/data-access-viewer/) for the site on coordinates (-1.314, 36.90). Monthly Daily average Global Horizontal Irradiance (GHI) in a Typical Meteorological Year (TMY) of solar radiation data collected over a period of 22 years (1983-2005) was obtained.

The daily GHI values were resolved into hourly irradiance values by using the HDKR model shown in Equation 15 for estimating solar radiation falling on a tilted surface over a given time step. A Solar Water Heating System capable of meeting the demand at the hostel was then designed and sized based on hourly energy balance and cost minimization. The SWH System for the hostel was designed by taking into account prevailing load, available solar radiation and conversion technology. Hourly energy production by the SWHS was simulated on Excel andIt was assumed that the daily hot water demand was constant for the whole year. Flat plate collector type of SWH system (MEGASUN GREECE-DIRECT MS) with storage tanks were chosen for this study.

3.0 Results

3.1 Solar Thermal Load

The daily hot water demand profile was estimated as shown in Fig 1where it was found that peak usage occurs between 0500 hrs. and 0700 hrs. Another peak demand is experienced between 1700hrs and 1900hrs.

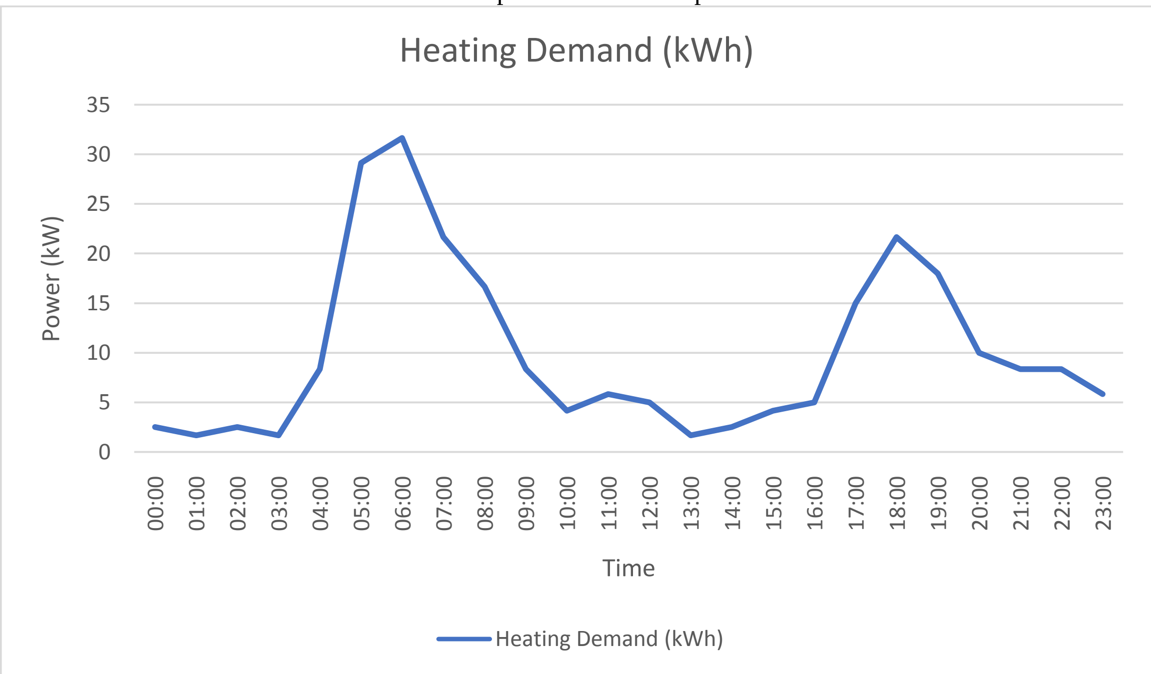

Figure 1. Daily Hot Water Demand Profile

3.2 Solar resource

Annual averages were downloaded from NASA surface meteorology and Solar Energy database.

Fig 2 shows the monthly average solar irradiation values for the site recorded over a period of 22 years which were used to generate a corresponding Typical Meteorological Year (TMY) for the site.

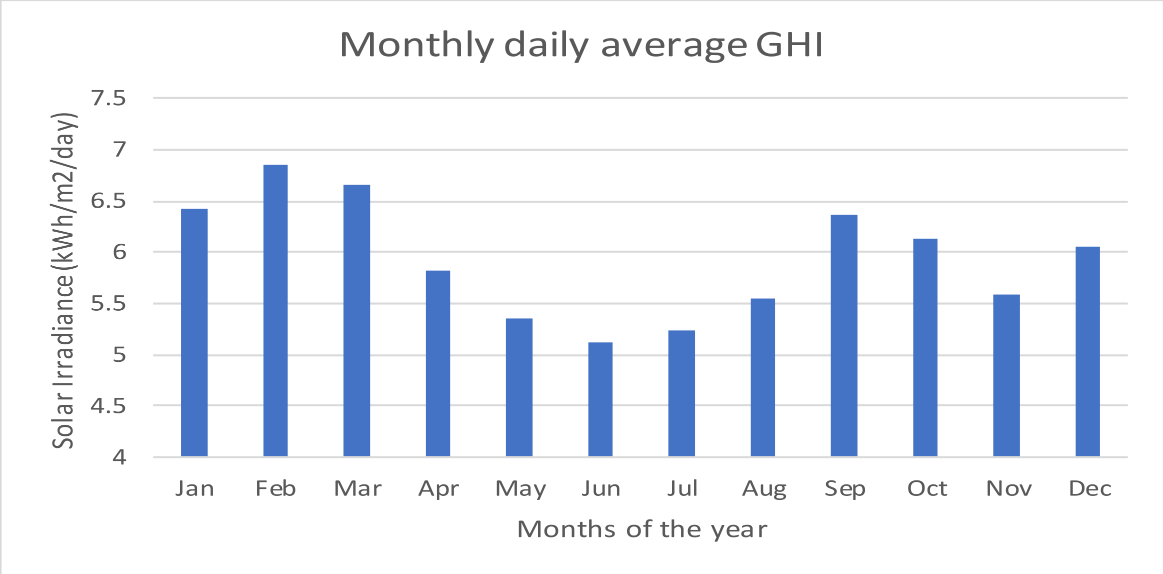

Figure 2. Solar GHI resources for the site courtesy of NASA [10].

3.3 SWHs design and optimization

Table 1 presents the technical and geometric parameters of MEGASUN GREECE-DIRECT MS SWHs which was selected for the study.

Table 1. Technical specifications for MEGASUN GREECE MS 300

MEGASUN GREECE-DIRECT MS 300 SPECIFICATIONS	
Collector Area (m^2)	6.2115
Storage Tank Volume (L)	300
Conversion Efficiency	40%
Test Pressure (Bars)	10

Hourly System operation as simulated using excel showed that the most optimal SWH system consisted of 22 units of the chosen solar collectors and storage tanks. The total annual energy generation by the system was found to be 85415 kWh. This results to a deficit of 954.955 kWh which is met by electric back up water heater. It was assumed that the heating load remained constant for all the months of the year. Figs2 and 3 show simulated operation characteristics of the designed system for February and June which are months with highest and lowest solar irradiance respectively.

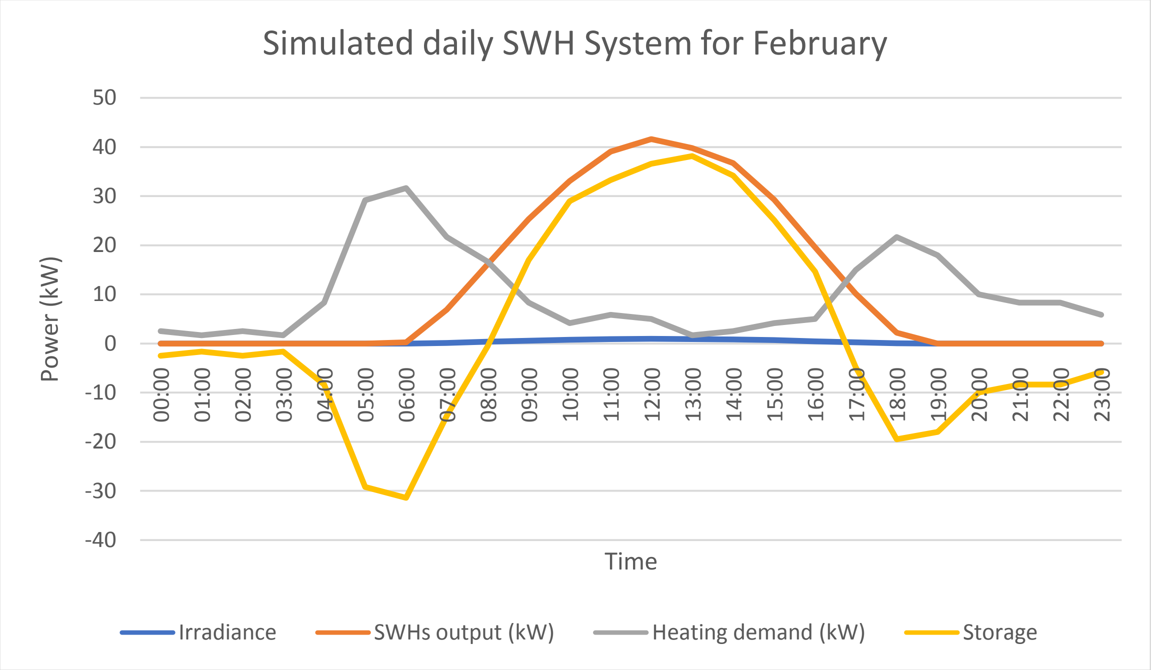

Figure 3. Simulated daily SWH system operation for February.

As shown in Fig 3, power supply and demand are greatly mismatched. There is low demand during the day when the heating system is productive. For this month, all the hot water demand is met by the SWH system.

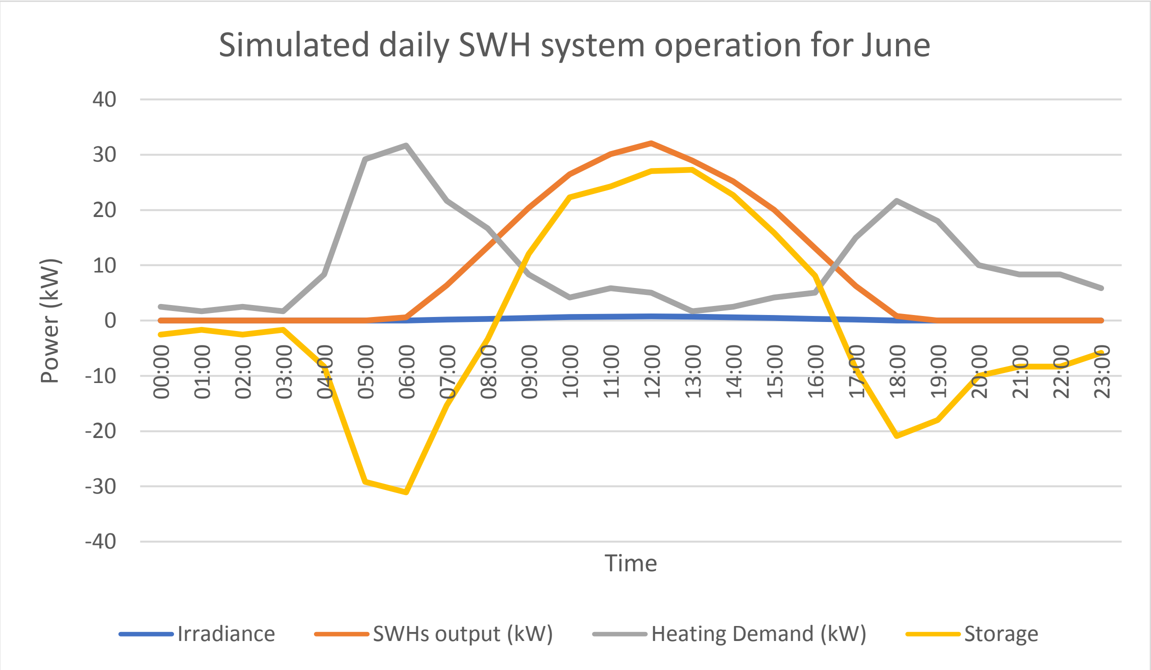

Figure 4. Simulated daily SWH system operation for June.

During the month of June, there is a supply shortage of 480.6 kWh in meeting demand which is met by use of back up electrical water heaters. Some months with high solar radiation recorded net excess system output while months with low irradiance levels have power supply deficit as shown in Fig 4.

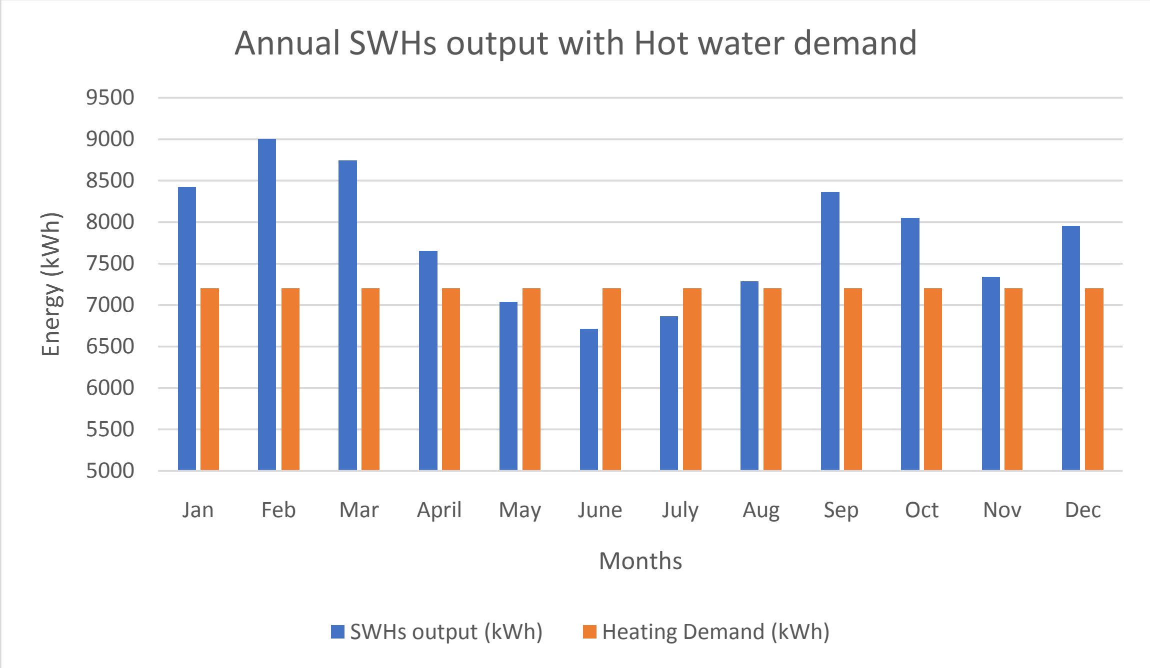

Figure 5. Annual System output vs hot water demand.

As shown in Fig 5, the system is highly oversized for the months of January, February, March and September. However, reducing the system size will lead to serious under sizing for the low irradiance months of May, June and July.

The Cost of Energy for this system is Ksh 6.45/kWh which is significantly lower than the cost of electricity from the grid at Ksh 18/kWh for this class of consumer. Any addition or reduction of the system size results to an increase in the CoE hence the proposed size is ideal for meeting assessed demand.

4.0 Conclusion

In this paper, a Solar Water Heating system for meeting the hot water demand of a students' hostel was designed and sized by considering hourly performance. The most optimal system was found to consist of 22 flat plat collector units each with a storage capacity of 300 L. The system can meet 100 % of hot water demand during months with high solar radiation. Simulated annual heating energy output of the system was found to be 85,415 kWh of heat energy. An annual energy deficit of 954.95 kWh is met by using grid electricity. Economic analysis of the system revealed that the cost of energy derived from it is Ksh 6.45/kWh. This price per unit energy is lower than the grid price of Ksh 18/kWh. This study has therefore shown that solar thermal energy can provide a reliable low cost means of meeting hot water demand for the hostel under study and the same design approach may be extended to similar facilities.

References

[1]. A. Kumar andS. Shukla, A Review on Thermal Energy Storage Unit for Solar ThermalPower Plant Application,*Energy Procedia* 74,2015,462 – 469. DOI: 10.1016/j.egypro.2015.07.728

[2]. J. Twidell and T. Weir,*Renewable Energy Resources* (Taylor & Francis 270 Madison Ave, New York, NY 10016, USA, 2006)https://www.taylorfrancis.com/books/9781135803209

[3]. E. Piertese-Quirjins, H. Loon, H. Beverloo, J. BlomandE. Vreeburg, Validation of non-residential cold and hot water demand model assumptions,*Procedia Engineering 70*,2014, 1334 – 1343. http://resolver.tudelft.nl/uuid:ea5858ea-e0b0-4360-a0a5-01dbb4605cec

[4]. B. Levesque, M. lavoieand J. Jolly, Residential water heater temperature: 49 or 60 degrees Celsius? *Can J Infect Dis. 15(1)*,2004, 11–12. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2094925/

[5]. J. Suh and Y. Choi,Methods for Converting Monthly Total Irradiance Data into Hourly Data to Estimate Electric Power Production from Photovoltaic Systems: A Comparative Study. *Sustainability*9**,** 2017, 1-19.

[6]. J.A. DuffieandW.A. Beckman, *Solar Engineering of Thermal processes 4th edition* (Wiley, New York, NY, 2013)..https://www.wiley.com/en-ke/Solar+Engineering+of+Thermal+Processes,+4th+Edition-p-9780470873663

[7]. D.G. Erbs, S.A Klein, andJ.A. Duffie, Estimation of the diffuse radiation fraction for hourly, daily, and monthly-average global radiation, *Solar Energy*, *28*, 1982, 293-302.

[8]. S.Liua, B. Haoa, X. Chenb, C.Yaoa and W. Zhouc, Analysis on limitation of using solar fraction ratio as solar hot watersystem design and evaluation index,*Energy Procedia 70*, 2015, 353 – 360.

[9]. ERC. (2012). Energy (Solar Water Heating) Regulations, Nairobi: Energy Regulatory Commission.https://renewableenergy.go.ke/index.php/news/3

[10]. National Aeronautic Space Administration. (n.d). NASA Surface Meteorology and Solar Energy. Retrieved from https://eosweb.larc.nasa.gov/cgi-bin/sse/sse.cgi?skip@larc.nasa.gov+s01#s01

[11]. M.J. Ko, Analysis and Optimization Design of a Solar Water HeatingSystem Based on Life Cycle Cost Using a Genetic Algorithm. *Energies*8, 2015, 11380-11403.

[12]. T. Mori and A. Kawamura, Design of solar water heating system for detached house in cold climate area. *Energy Procedia***48**, 2014, 1393 – 1400.