Abstract—Kenya has tremendous potential for solar energy due to its proximity to the Equator. The country receives an estimated 4 to 6 kWh per square meter per day of solar insolation. Solar energy can therefore be harnessed to meet the energy demands of this growing nation while protecting its environment. This paper proposes a solar household system for domestic households in Kenya with a monthly energy consumption of 200kWh to 400kWh. This system is implemented with a meter that can monitor the amount of energy used by the household from the solar system. This meter facilitates billing and payback. The economic viability of the solar system is determined using payback analysis and life cycle cost analysis.

Keywords—life cycle cost, payback, solar photo-voltaic, solar water heating

I. INTRODUCTION

The cost of electricity in Kenya is relatively higher than in the rest of the East African region, not to mention a number of African countries such as Egypt and South Africa. It also has a relatively low installed capacity of about 1,900MW [1]. A large part of the population that is connected to the national grid also suffers frequent power outages due to supply shortfalls.

A large-scale market-driven penetration of small PV systems with capacity of 12 – 50 watts power (Wp) consisting of low cost amorphous silicon modules and both mono- and polycrystalline silicon modules, has been established in Kenya. It is projected that by 2020, the installed capacity of solar photovoltaic systems will reach 10MW generating 22 GWh annually.

The demand for solar water heating (SWH) is projected to grow to more than 800,000 SWH units by 2020. This represents a growth rate of 20% per annum. This demand will mainly be from domestic, institutional and small commercial consumers spurred by the operationalization of the Energy (Solar Water Heating) Regulations, 2012 [2].

Solar electricity use is dominated by a rural middle class made up of small business owners, rural professionals that may not have access to electricity from the grid. Solar PV systems are widely used for household applications such as lighting, television, radio and cellular phone charging. However the significant role solar energy can play in urban and middle income households is yet to be realized. This paper presents a design of a residential solar system comprising of a Photo-voltaic (PV) system and solar thermal system for water heating. The target of this system is households in Kenya with an electricity consumption of about 200kWhs-400kWhs. This paper established a viable payback system from savings made from the solar system.

II. THE PHOTOVOLTAIC SYSTEM

Photovoltaic (PV) systems are powered by solar energy using solar modules. Photovoltaic cells are packed into modules that produce a specific voltage and current when illuminated. The generated electricity is stored in batteries and used for the purpose of lighting and small ac loads in domestic household application. These systems are most widely used in non-electrified rural areas and as reliable emergency lighting system for important domestic, commercial and industrial applications. The system comprises of Solar PV Module (Solar Cells), charge controller, battery and lighting and small ac loads system. The schematic of the home photovoltaic system is shown in below. The solar module is installed in the open on roof/terrace - exposed to sunlight and the charge controller and battery are kept inside a protected place in the house [3]. The two basic types of PV applications for homes are the stand-alone and the grid- connected systems. Stand-alone PV systems are used in areas that are not easily accessible or have no access to mains electricity grids. A stand-alone system is independent of the electricity grid, with the energy produced normally being stored in batteries. In the grid-connected applications, the PV system is connected to the local electricity network [4].

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Fig. 1 Typical domestic solar PV system.

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III. SOLAR WATER HEATING

Perhaps the most popular application of solar systems is for domestic water heating. The popularity of these systems is based on the fact that relatively simple systems are involved and solar water heating systems are generally viable. A solar water heater is a combination of a solar collector array, an energy transfer system, and a storage tank. The main part of a solar water heater is the solar collector array, which absorbs solar radiation and converts it to heat. This heat is then absorbed by a heat transfer fluid (water, non-freezing liquid, or air) that passes through the collector. This heat can then be stored or used directly. Thermosiphon systems, shown schematically in Fig. 2, heat potable water or transfer fluid and use natural convection to transport it from the collector to storage. The thermosiphoning effect occurs because the density of water drops with the increase of the temperature. Therefore, by the action of solar radiation absorbed, the water in the collector is heated and thus expands, becoming less dense, and rises through the collector into the top of the storage tank.

IV. SIZING OF PHOTO-VOLTAIC AND SOLAR WATER HEATING SYSTEM.

A. Energy Audit of sample households

Seven sample households that fall in the range of a monthly consumption of 200kWhs to 400kWhs, were selected from different locations within Nairobi. A site visit was done to the households. Power rating of major appliances and devices run in the household were determined. Through a questionnaire the inhabitants of the household gave information on the time period these power consuming devices are used daily. The total electricity used daily by the household in Kilowatt-hour (kWh) was calculated. The daily figure was then multiplied by 30 to get an average of the monthly electricity consumption of the household. The past electricity bills of the households were acquired to confirm their monthly electricity consumption. This information was recorded in a table for each household.

B. Estimation of the solar insolation available at the sites.

"Insolation" is the density of the energy that falls on a surface over some period of time such as an hour or a day (e.g. Wh / m² per hour/day). The solar insolation available at the site of the sample households was obtained from a report on:

Assessment of the solar radiation potential of the Thika and Nairobi area [5].

C. Sizing of the PV system

1) Calculation of Design Load and Energy Demand

   - Design Load (Pd)

   The design load is the instantaneous load for which the power conversion, distribution and protection devices should be rated, e.g. rectifiers, inverters, cables, fuses, circuit breakers, etc.

   \[ P_d = P_p (1 + K_g)(1 + K_c) \]

   Where:
   - Pd is the design load real power (W)
   - Pp is the peak load real power, derived from the load profile (W)
   - Kg is a contingency for future load growth (%)
   - Kc is a design margin (%)

   It is common to make considerations for future load growth (typically somewhere between 5 and 20%), to allow future loads to be supported. If no future loads are expected, then this contingency can be ignored. A design margin is used to account for any potential inaccuracies in estimating the loads, less-than-optimum operating conditions due to improper maintenance, etc. Typically, a design margin of 10% to 15% is recommended.

   - Design of energy demand (Ed)

   The design energy demand is used for sizing energy storage devices. From the load profile, the total energy (in terms of Wh) can be computed by finding the area underneath the load profile curve (i.e. integrating instantaneous power with respect to time over the 24h period). The design energy demand (or design Wh) can then be calculated by the following equation:

   \[ E_d = E_t (1 + K_g)(1 + K_c) \]

   Where:
   - Ed is the design energy demand (Wh)
   - Et is the total load energy, which is the area under the load profile (Wh)
2) Calculation of solar insolation on an Inclined Plane

Most PV arrays are installed such that they face the equator at an incline to the horizontal (for maximum solar collection). The amount of solar insolation collected on inclined surfaces is different to the amount collected on a horizontal surface.

The solar insolation at the optimal tilt angle can be estimated. The optimal tilt angle largely depends on the latitude of the site. At greater latitudes, the optimal tilt angle is higher.

Optimal tilt angle was calculated by:

\[ \beta_{opt} = 3.7 + 0.69|\phi| \]  

(3)

Where:
- \( \beta_{opt} \) is the optimal tilt angle (deg)
- \( \phi \) is the latitude of the site (deg)

To calculate the solar insolation at the optimal tilt angle:

\[ G(\beta_{opt}) = \frac{G(0)}{1 - 4.46 \times 10^{-4} \beta_{opt} - 1.19 \times 10^{-4} \beta_{opt}^2} \]  

(4)

Where:
- \( G(\beta_{opt}) \) is the solar insolation on a surface at the optimal tilt angle (Wh/m²)
- \( G(0) \) is the solar insolation on the horizontal plane (Wh/m²)
- \( \beta_{opt} \) is the optimal tilt angle (deg)

3) Sizing of battery bank

The “days of autonomy,” were determined. That is, the number of days the system is expected to provide power without receiving an input charge from the solar array.

\[ B_c = \frac{E_d \times D_o A}{V_{dc} \times D_o D} \]  

(5)

Where:
- \( B_c \) is the minimum daily battery capacity (Ah)
- \( E_d \) is the design daily energy (Wh)
- \( D_o A \) is the days of autonomy (in hours)
- \( V_{dc} \) is the nominal dc system voltage (V)
- \( D_o D \) is maximum depth of discharge (%)

A battery Ah capacity that exceeds the minimum capacity calculated above was selected.

The number of batteries wired in parallel required was determined by: dividing the total battery capacity by the battery amp-hour rating of the selected battery and round off to the next highest number.

The number of batteries wired in series was determined by dividing the nominal dc system voltage (12V, 24V or 48V) by the battery voltage and round off to the next highest number.

To determine the total number of batteries required, the number of batteries in parallel was multiplied to the number of batteries in series.

4) Sizing of the PV array

The total amperage required from your solar array was determined by:

\[ P_{V_A} = \frac{Bc \times B_e \times SF}{G} \]  

(6)

Where:
- \( Bc \) is the daily demand on battery capacity (Ah)
- \( G \) is the solar radiation at the optimal tilt angle (Wh/m²)
- \( B_e \) is the battery charging efficiency (typically 80 – 90%)
- \( SF \) is the soiling factor for installation (typically 0.9 – 1.0)

The maximum module temperature was estimated and the rating reference temperature (typically 25°C)

The required charging voltage from PV array was determined by:

\[ P_{Vv} = V_{dc} - (V_{dc} \times temperature \ coefficient \times (Max. \ Temperature - Reference \ Temperature)) \]  

(7)

The charging power from PV array was determined by:

\[ P_{Vw} = 1.2 \times P_{Vv} \times P_{VA} \]  

(8)

The factor 1.2 accounts for wiring losses, charge controller loss, PV module overrating and other losses

An appropriate PV modules for the system voltage is then selected.

The number of PV modules in series by was determined by dividing the module rated voltage from required charging voltage and rounding up.

The number of PV modules in parallel was determined by dividing the module rated current by required charging current and rounding up.

The total number of modules in array was determined by multiplying the number of modules in series with the number of modules in parallel.

\[ \text{nominal power output of system (W)} = \text{nominal power rating of module (W)} \times \text{Total number of modules} \]  

(9)

5) Sizing of Charge Controller and Inverter

The short circuit current of PV module selected was looked up.

The charge controller minimum power current = short circuit current of PV module x number of modules in parallel \( \times 1.25 \)

An appropriate charge controller was selected

\[ \text{Inverter minimum power size} = P_d \times 1.25 \]  

(10)

An appropriate inverter was selected

The factor 1.25 is the safety factor for continuous operation

6) A code was generated in matlab to carry out the sizing procedure

D. Solar Water Heater sizing

According to principle Hottel-Whillier the useful energy output of a collector can be represented as:

\[ Q_{coll} = Ac \cdot Fr \cdot (G - U_L \cdot (T_{f,i} - T_a)) \]  

(11)

Where:
Qcoll: is the Heat energy in the collector (Wh/day)
Ac: is the Collector area (m$^2$)
Fr: is the removal factor of solar collector
G: is the solar radiation (Wh/m$^2$/day)
U_L: is the Coefficient of thermal losses from solar collector
T_f,I: is the Inlet water temperature tor solar collector (°C)
Ta: is the air or ambient temperature (°C)

\[ Q_{load} = m_LC_p(T_S - T_L) \]  

Where:
\( m_L \): is the mass flow rate (kg/sec)
\( C_p \): is the specific heat capacity of water, 1.161 \times 10^{-3} \text{kWh/kg.°C} \)
\( T_S \): is the average temperature of hot water in the storage tank (°C)

\[ Q_s = m_sC_p\left(\frac{T_S - T_a}{\Delta t}\right) \]  

Where:
\( Q_s \): is the Energy per unit time in the storage tank (W)
\( \Delta t \): is the change in time in hours
It is assumed that Qloss is 20% of energy in the storage tank, Qs

Therefore:
\[ Q_s = Q_{coll} - Q_{loss} - Q_{load} \]  

Based on the equations above a code was generated in matlab to size the system required for each household.

V. DESIGN OF METER

A. Hot water management and monitoring

A water flow sensor was used. It consists of a plastic valve body, a water rotor, and a hall-effect sensor. When water flows through the rotor, it rotates. Its speed changes with different rates of flow. The hall-effect sensor outputs the corresponding pulse signal. The sensor produces a series of pulses that are counted by the microcontroller according to the calibration. Since it gives the speed of the flow, the volume is then calculated from it by taking the speed in litters per second and adding up the volume every second.

For both the purposes of determination of energy saved in heating the water as well as user feedback for decision making, a temperature sensor, DS18B20 was used. This sensor outputs analogue values of temperature to the serial port of the microcontroller. These values are then output to the LCD display as well as used to calculate water savings.

To allow the user to know the amount of water in the hot water tank an ultrasonic sensor is employed. This sensor is able to determine the depth of water in a tank whose dimensions is known. Based on this the amount of water was calculated and outputted through an LCD display.

B. Electrical energy management and monitoring

In this system the voltage and current levels are measured at intervals of a second. The implementation of voltage measurement is through voltage divider to allow a maximum 3V from the system battery 12V to reach the microcontroller. A hall effect current sensor is used to measure the current being drawn by the load. The power is then computed by multiplying the two to get the wattage. This value is used to compute the kilowatt hours over the time it was measured.

Relay switches are used to connect the given household to and from the system.

VI. DETERMINATION OF OPTIMUM SIZE OF SYSTEM

A. Photovoltaic system.

For each sample household, PV systems were sized to meet 5%, 10%, 15%, 25%, 50% and 100% of the estimated energy load.

The cost of each system was estimated using data sheets and price lists obtained from Power Technics, a major solar equipment distributor in Kenya. Through analysis of the sizing of various components in the PV system and their cost, it was evident that the inverter and charge controller cost varied greatly due to difference in peak power. With cost as a major factor, it was determined that a 12V photovoltaic system, with a peak power demand of 400W and energy demand of 1000Wh costing approximately 100,000ksh could be used.
B. Solar water heating system

From the sampled households, it was determined that the average number of people in a household was five. The number of people in a household determines the daily hot water requirements for that household. The hot water requirements are used to determine the most suitable size of collector. The collector size calculated was 2.004m$^2$. Based on the price list given by Solimpex, a solar water heater (SWH) distributor in Kenya, a T200 SWH with an output capacity of 250 liters/day and a collector area of 2.5m$^2$ costs 150,000Ksh.

VII. PAYBACK PERIOD ANALYSIS

A. Payback period for photovoltaic system alone

Monthly Saving

\[\text{Monthly Saving} = \text{Energy demand per month (KWh)} \times \text{cost of electricity per month per kWh (ksh)}\]

\[\text{Monthly Savings} = \frac{\text{Capital Cost}}{\text{Monthly Savings}}\]  \hspace{1cm} (13)

For the selected system:

\[\text{Payback period (in months)} = \frac{100,000}{1.000 \times 30 \times 22} = 151.52 \text{ months} = 12.63 \text{ years}\]

B. Payback period for solar water heating system alone

- From the sample households, the average daily hot water load =5.174kwh
  - In a month assuming a 30 day month, average hot water load= 155.22 kWh
  - Payback for a load of 155kwh is:
    \[\text{Payback period (in months)} = \frac{155,000}{155 \times 22} = 3.67 \text{ years}\]
  - For a household with an energy load of 400Kwh per month, and hot water load is 50%
    \[\text{Payback for a load of 200kwh is:}\]
    \[\text{Payback period (in months)} = \frac{150,000}{200 \times 22} = 34.09 \text{ months} = 2.84 \text{ years}\]
  - For a household with an energy load of 200Kwh per month, and hot water load is 50%
    \[\text{Payback for a load of 100kwh is:}\]
    \[\text{Payback period (in months)} = \frac{150,000}{100 \times 22} = 68.18 \text{ months} = 5.68 \text{ years}\]

C. Payback period for PV system and SWH system

From the large payback period of the photo-voltaic system and the relatively smaller payback period of the solar water heating system, it has been noted that it is necessary to combine the two systems so together they can have a viable payback period.

Photovoltaic energy load per month: 30kWh
Photovoltaic system total cost: 100000

<table>
<thead>
<tr>
<th>Hot water load per month (kWh)</th>
<th>Total energy load (kWh)</th>
<th>Capital cost of both systems</th>
<th>Payback in months</th>
<th>Payback in years</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>130</td>
<td>250000</td>
<td>87.41</td>
<td>6.78</td>
</tr>
<tr>
<td>150</td>
<td>180</td>
<td>250000</td>
<td>63.13</td>
<td>5.26</td>
</tr>
<tr>
<td>200</td>
<td>230</td>
<td>250000</td>
<td>49.4</td>
<td>4.12</td>
</tr>
</tbody>
</table>

VIII. LIFE CYCLE COST (LCC) ANALYSIS

The LCC of an item consists of the total costs of owning and operating an item over its lifetime, expressed in today’s money.

The LCC of the system includes the sum of all the present worth (PWs) of the individual components. In this case the LCC of the combined PV and solar water heating system includes the PWs of the PV modules, storage batteries, inverter and charge controller and the solar water heating system.

The lifetime N of all the items is considered to be 20 years, except that of the battery which is considered to be 5 years. Thus, an extra 3 groups of batteries have to be purchased, after 5 years, 10 years, and 15 years.

The current inflation rate in Kenya is 6.43% and the average discount or interest rate \(d\) is 8.5%.

\[PW = \text{Cost} \left(1 + \frac{i}{1 + d}\right)^N\]  \hspace{1cm} (14)

Where, \(N=\text{number of years}\)

Table II shows the calculated LCC of the system.
TABLE II
LCC FOR SYSTEM FOR A MONTHLY LOAD OF 130KWH, 180KWH AND 230KWH

<table>
<thead>
<tr>
<th>Monthly load (kWh)</th>
<th>ALCC (ksh) (N=5)</th>
<th>Ksh/kWh (N=5)</th>
<th>ALCC (ksh) (N=7)</th>
<th>Ksh/kWh (N=7)</th>
<th>ALCC (ksh) (N=8)</th>
<th>Ksh/kWh (N=8)</th>
<th>ALCC (ksh) (N=20)</th>
<th>Ksh/kWh (N=20)</th>
</tr>
</thead>
<tbody>
<tr>
<td>130</td>
<td>68447.34</td>
<td>43.8765</td>
<td>49823</td>
<td>31.9378</td>
<td>44007.15</td>
<td>28.21</td>
<td>19657.33</td>
<td>12.6</td>
</tr>
<tr>
<td>180</td>
<td>68447.34</td>
<td>31.6886</td>
<td>49823</td>
<td>23.0662</td>
<td>44007.15</td>
<td>20.37</td>
<td>19657.33</td>
<td>9.1</td>
</tr>
<tr>
<td>230</td>
<td>68447.34</td>
<td>24.7998</td>
<td>49823</td>
<td>18.0518</td>
<td>44007.15</td>
<td>15.944</td>
<td>19657.33</td>
<td>7.12</td>
</tr>
</tbody>
</table>

TABLE III
THE ALLC AND UNIT ELECTRICAL COST

<table>
<thead>
<tr>
<th>Component</th>
<th>Cost</th>
<th>Purchased after N-years</th>
<th>PW</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV array</td>
<td>48000</td>
<td>0</td>
<td>48000</td>
</tr>
<tr>
<td>Battery set 1</td>
<td>32000</td>
<td>0</td>
<td>32000</td>
</tr>
<tr>
<td>Battery set 2</td>
<td>32000</td>
<td>5</td>
<td>29061.74</td>
</tr>
<tr>
<td>Battery set 3</td>
<td>32000</td>
<td>10</td>
<td>26393.27</td>
</tr>
<tr>
<td>Battery set 4</td>
<td>32000</td>
<td>15</td>
<td>23969.82</td>
</tr>
<tr>
<td>Inverter and charge controller</td>
<td>20000</td>
<td>0</td>
<td>20000</td>
</tr>
<tr>
<td>SWH system</td>
<td>15000</td>
<td>0</td>
<td>150000</td>
</tr>
<tr>
<td>TOTAL LCC</td>
<td></td>
<td></td>
<td>329424.83</td>
</tr>
</tbody>
</table>

It is useful to calculate the LCC of a system on an annual basis. The annualized LCC (ALCC) of the PV system in terms of the present day ksh can be calculated as:

\[
ALCC = \frac{LCC \left(1 - \left(\frac{1+i}{1+d}\right)^{N}\right)}{1 - \left(\frac{1+i}{1+d}\right)^{N}} \quad (15)
\]

ALCC can be used to determine unit electrical cost.

\[
\text{unit electrical cost} = \frac{ALCC}{12 \times \text{EEL per month}} \quad (16)
\]

Where N= lifespan of the project or payback period

IX. CONCLUSION

From the life cycle cost analysis, one can conclude that a viable system is one with a unit electrical cost less than the current unit electrical cost of 22ksh/kWh. From the payback analysis done it is evident that a combined system is more viable. The unit electrical cost calculated in the life cycle cost analysis can be used to price the energy supplied to a household from the photovoltaic system and solar water heating system. 1kWh should be the same price in both systems so the solar water heating system can contribute towards the payback for the photovoltaic system. For a payback period of seven years, a solar system that meets 230kWh monthly of the energy demand of the household, has a unit electrical cost of 18.0518ksh/kWh. For a payback period of eight years, solar systems that meets 180 kWh monthly and 230kWh monthly of the energy demand of the household have a unit electrical cost of 20.37ksh/kWh and 15.944ksh/kWh respectively.

REFERENCES