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Economic investigation of low cost Organic Rankine Cycle incorporated in a combined solar photovoltaic cum thermal plant

Abel C. Yabo¹, George Adwek^{1,4}, Boxiong Shen^{1,5}, Augustine Makokha², Zachary Siagi², Patrobers Simiyu³, Kemunto M. Cecilia¹, Chebet -Chepsaigutt⁴, Paul Ndolo⁴ and Shimmon John⁴

¹ School of Energy and Environmental Engineering, Hebei University of Technology, Tianjin, China;

² School of Engineering, Moi University, Eldoret-Kenya;

³ School of Electrical and Electronic Engineering, North China Electric Power University, Beijing;

⁴ Sunpawa Energy, KCIC Centre, Ole Sangale Road, Nairobi-Kenya.

⁵ Email: shenbx@hebut.edu.cn

Abstract. Current rise in small scale solar thermal combined electricity generation water heating in Kenya has corresponded with demand growth for power supply in areas poorly served by the national grid. The potential technical approach to this increasing demand encourages the use of PV (Photovoltaic) solar collectors coupled with ORC (Organic Rankine Cycle) system. This paper uses Aspen plus software in modelling ORC system. Thika (00, 370, 41'E) climatic conditions is selected for the present case study to examine performance and cost of the system. The system comprises of PV collectors, oil storage unit, pump, and a small scale ORC engine using an expander. The model evaluates the performance of the system under the change in environmental temperature (Thika town conditions adopted) or varying the mass flow rate of heat transfer fluid (HTF). The results indicate that using Therminol oil 55 as HTF and R245fa (1,1,1,3,3-pentafluoropropane) as the working fluid and a collector heat source temperature of 163.5°C delivered an output power of 15kW with the overall efficiency attained as 8.5%. The proposed system is intended to be potentially suited in Kenyan counties with good solar irradiation and without (or with high cost) access to the national grid electricity supply. Detailed cost analysis of the system was carried out in using Levelized Cost of Electricity (LCOE) order to determine the system viability and payback period and Depreciated Payback Period (DPP). For super heater outlet temperature of 130°C, mass flow rate 3000kg/h, the specific cost of 2kW system is 12,073 \$/kW with a LCOE of 13.5c\$/kWh and a payback period of 10 years. While for 15kW system with the LCOE of 12.2 c\$/kWh, specific installed cost is about 8,068 \$/kW; the payback period is approximately 6 years.

1. Introduction

Due to current shortage of fossil fuels and serious environmental pollution challenges as a result of growing industrialization, utilization and exploration of waste and renewable energy has been receiving increasing attention from both the governments and several organizations. Various thermodynamic cycles like ORC, super critical CO₂ cycle, kalina cycle, and heat pipe technology have been proposed to ease such issues [1-2]. ORC is a well proven technology for solar power generation,



it can be operated economically due to its special framework conditions [3-4]. Taking into account recent regulations and policies restraining fossil fuel usage, global energy related CO₂ emissions are projected to rise by 46% in 2040 from 31 billion metric tons in 2010. ORC technology is based on principles of renewable energy with potential of reducing greenhouse gases emissions (GHGs) caused by fossil fuels. In other words, ORC is extensively used to generate power in an environmentally friendly manner [4]. It is relatively mature, commercially available technology and it is exceptionally suitable for conversion of heat at temperatures below 400⁰C to a useful work at a power output ranging from kW to tens of MW [5]. ORC uses organic fluids having a liquid vapor phase change as the working fluid. The working fluid selection for ORC systems has received much attention recently as well as interest in multi component fluid mixtures as a result of opportunities they offer in thermodynamic performance improvement [5]. Some of the properties considered in choosing working fluids used in ORC system are: higher molecular mass, higher mass flow compared to water, high temperature stability, higher vapor pressure, lower boiling point, thermodynamic performance, low ODP (ozone depletion potential), low GWP (Greenhouse Potential), environmental impact, safety, and acceptable evaporating pressure [6]. As indicated in the report by [7], there is a considerable percentage of renewable energy resources in Kenya that are unexploited. Kenya has utilized only approximately 30% and 4% of its hydropower and geothermal resources respectively and a much smaller fraction of proven wind and solar potential. In Kenya, like many other developing countries, the non-commercial biomass serves a bigger role in energy supply especially the domestic and residential sector (Figure 1a, b).

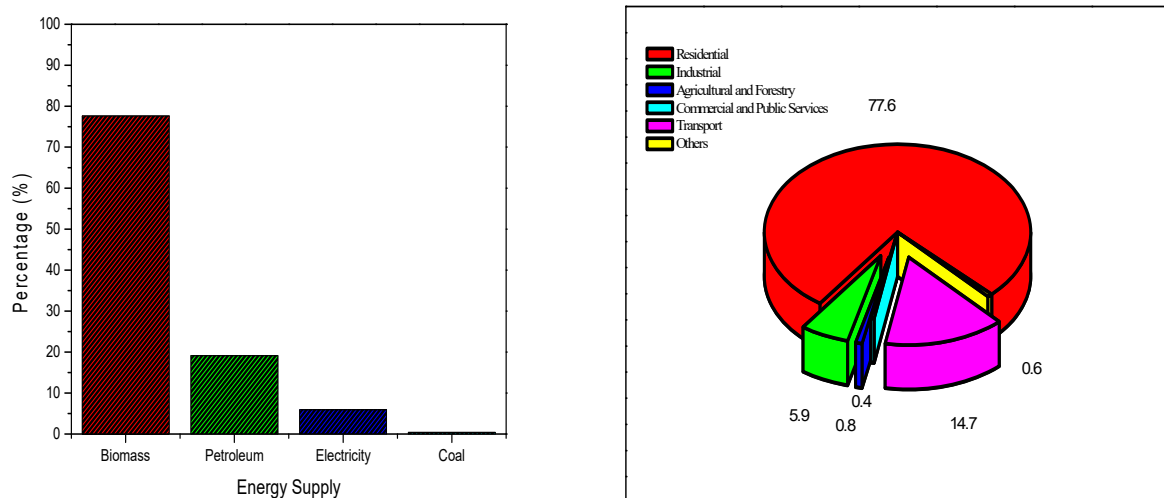


Figure 1. (a). Energy supply in Kenya; (b). Energy consumption by sector.

In recent years, the ministry of energy in Kenya has developed various policies and regulations aimed at promoting government priorities specially to create an enabling environment for private sector led growth as well as increasing approach and coverage of energy supply and promotion of renewable energy. Kenya is enriched with various energy resources such as; Hydropower, geothermal, biomass, solar, and wind. Kenya receives an average of about 5 kW/m²/day of solar insolation which is equivalent to 250 million tons of oil (Toe) per day. Table 1 shows the Direct Normal Irradiation in Kenya.

Table 1. Analysis of direct normal irradiation (DNI) in Kenya [8].

| DNI (kW/m ² /day) | Area (Km ²) | DNI (kW/m ² /day) | Area (Km ²) |
|---------------------------------|----------------------------|---------------------------------|----------------------------|
| 3.50-3.75 | 41721 | 5.50-5.75 | 33848 |
| 3.75-4.00 | 61515 | 5.75-6.00 | 20211 |
| 4.00-4.25 | 140326 | 6.00-6.25 | 24675 |
| 4.25-4.50 | 177347 | 6.25-6.50 | 33690 |
| 4.50-4.75 | 137572 | 6.50-6.75 | 22468 |
| 4.75-5.00 | 96199 | 6.75-7.00 | 16240 |
| 5.00-5.25 | 62364 | 7.00-7.25 | 6736 |
| 5.25-5.50 | 48826 | 7.25-7.50 | 2656 |

The residential sector in Kenya consumes about 820GWh of electricity annually for water heating; growing electricity demand is putting a strain on power infrastructure. Demand of water heating occurs during the morning and evening increasing the overall peak load. This necessitates dispatch of expensive thermal power. Use of Solar Water Heating (SWH) systems can lower the peak demand originating from the need for water heating by domestic, commercial and institutional users. The current cost of a typical 100-liter solar water heating system is \$ 1,500 which is unaffordable to many households, there is low awareness regarding SWH technology and its financial benefits [7].

2. Methodology

In the present study, analysis of a solar ORC system designed to supply hot water at temperature 55°C and produce electricity for approximately 1500 people was carried out using Aspen plus v8.0. In order to determine the collector size, the required heat output was determined from the simulation model. Since solar insolation plays a crucial part in Solar ORC system, Thika, Kenya (0°, 37°, 41'E) weather conditions (see Figure 2a, b) have been used in the analysis. This weather condition was therefore used in calculating the collector area. In addition, ORC efficiency, power output and, mass flow rate was determined in the simulation process.

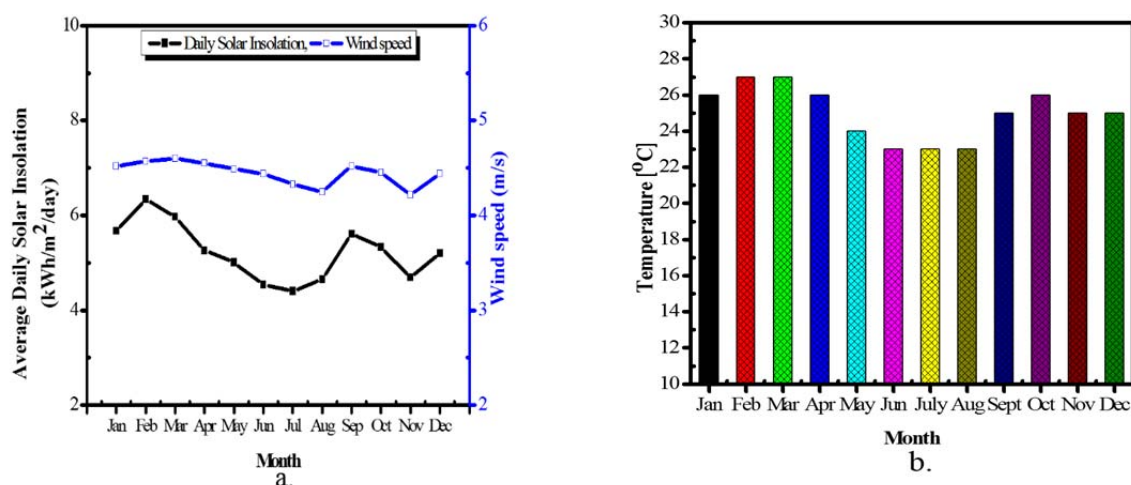


Figure 2. (a). The average Monthly daily solar insolation and wind speed for Thika, **(b)** The average monthly daily temperature for Thika..

The mean monthly daily solar insolation range in Thika is $4.4\text{kWh/m}^2/\text{day}$ - $6.37\text{kWh/m}^2/\text{day}$, mean monthly temperature of 24°C with an average of 8hrs of sunlight per day.

3. Solar ORC technology

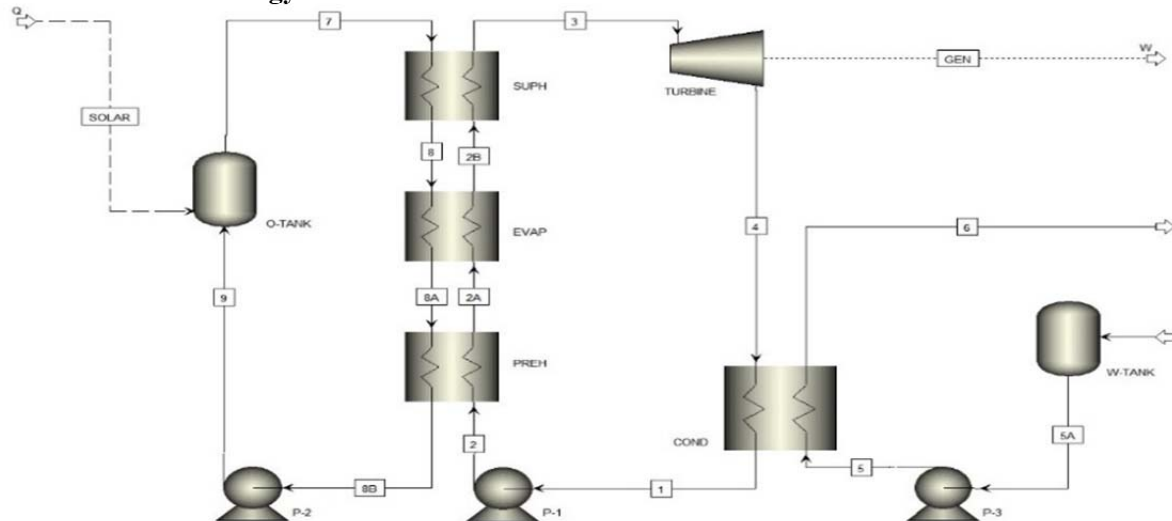


Figure 3. Schematic diagram of the organic Rankine cycle driven by solar energy.

Figure 3 shows the model of solar ORC used in this study. The system can be described as follows- low temperature heat transmitting fluid (HTF) is heated to high temperature using solar energy through PV collectors. High temperature HTF is used to generate high temperature and high pressure organic fluid vapor through heat exchanger and HTF coming out of the evaporator is pumped back to the oil-tank. The condition of organic fluid vapor at inlet of turbine is superheated, high temperature and high pressure organic fluid vapor from the evaporator is expanded through an expander to generate power. Organic fluid is condensed in the condenser which then flows to the pump to complete the cycle [9]. The HTF used is Therminol 55 and organic fluid used in the ORC cycle is R245fa. The organic fluid thermodynamic condition is a crucial factor to consider (not in this paper's scope) and its thermodynamic properties are shown in Table 2. The hot water exit temperature was set at 55°C .

Table 2. Properties of the working fluid R-254fa.

| Thermodynamic properties | R-254fa |
|-------------------------------------|---------|
| Density(kg/m^3) | 1352 |
| Molar Weight(kg/kmol) | 134.05 |
| BP($^\circ\text{C}$) | 15.3 |
| T _c ($^\circ\text{C}$) | 154.1 |
| PC (bar) | 36.4 |
| ASHRAE 34 | B1 |
| Ozone Depletion Potential | 0 |
| Global Warming Potential | 820 |

4. Thermodynamics

For simplicity, several reasonable assumptions were considered for the analysis of the model's overall performance of the systems and sub systems. The assumptions were as shown in Table 3.:

Table 3. Assumptions.

| Parameters | Value | Units |
|------------------------------------------------------------|-------|-------|
| Solar collector temperature t_7 (indicated in Figure 3.) | 163.5 | °C |
| Isentropic efficiency for the turbine | 80 | % |
| Pump isentropic efficiency | 75 | % |
| Electrical generator efficiency | 95 | % |
| Ambient temperature T_0 | 25 | °C |
| Pinch point temperature of the evaporator & condenser | 5 | °C |
| Dead state pressure | 1 | bar |

All the thermodynamics systems and processes are at steady state, the energy balance for each of the components in the system based on the first law of thermodynamics can be written as:

$$\sum \dot{m}_i - \sum \dot{m}_o = 0, \quad (1)$$

$$(\dot{Q} - \dot{W}) + \sum \dot{m}_i h_i - \sum \dot{m}_o h_o = 0 \quad (2)$$

Where subscripts i and o represent inlet and outlet respectively. \dot{m} is the mass flow rate. h -the specific enthalpy of the system streams. Furthermore, \dot{Q} and \dot{W} represent the heat transfer across the component boundaries. The restraints of energy assessment can be overcome applying exergy analysis method which deals with the conversion of energy along with the second law of thermodynamics, this assists in reducing existing efficiencies. The exergy balance in the ORC components at the steady state can be determined by applying the following general equation [10].

$$\dot{E}x_{d,k} = \dot{E}x_Q - \dot{E}x_W + \sum \dot{m}_i ex_i - \sum \dot{m}_o ex_o \quad (3)$$

$\dot{E}x_{d,k}$ - exergy destruction rate in device k; $\dot{E}x_Q$ -exergy rate due to heat transfer; $\dot{E}x_W$ -exergy rate due to work; $\dot{m}_i ex_i$, $\dot{m}_o ex_o$ -exergy rate in and out of the system

$$\dot{E}x_Q = \sum (1 - \frac{T_0}{T}) Q \quad (4)$$

T_0 -dead state temperature (when the system is in equilibrium with the environment); T is the boundary temperature in which the heat transfer occurs

$$\dot{Q}_u = \dot{m}_c (C_{p,o} T_o - C_{p,i} T_i) \quad (5)$$

For a single collector, useful collected energy rate is given by; C_p -is the specific heat capacity, \dot{m}_c -mass flow rate in the collector, T_o , T_i are the outlet and inlet temperature of the collector respectively. From the collector equation energy balance, the area of the collector can be determined as follows;

$$\dot{m}_c (h_o - h_i) = G_b \cdot \eta_c \cdot A_c \quad (6)$$

G_b , η_c , A_c are global radiation on surface, efficiency of the collector and A_c is the area of the collector respectively [11]. The net efficiency of the system is calculated from the equation;

$$\eta_{net} = \eta_c \cdot \eta_{ORC} \quad (7)$$

The exergy input

$$Ex_{sun} = G_b \cdot A_c \left[1 + \frac{1}{3} \left(\frac{T_o^4}{T_s^4} \right) - \frac{3}{4} \left(\frac{T_o}{T_s} \right) \right] \quad (8)$$

$$T_s = 5800K$$

Net electrical exergy efficiency is defined as:

$$\eta_{ex,el} = \frac{W_{net}}{E_i} \quad (9)$$

The improvement potential in the exergy destruction of component k, is given by;

$$IP_k = (1 - \eta_{ex,el}) \dot{E}x_{d,k} \quad (10)$$

5. Results

The optimum working condition was obtained at a temperature range of 129°C-131°C with the best temperature as 130°C at evaporator exit as shown in Table 4 and the efficiencies and temperature variation are as illustrated in Figure 4.

Table 4. Simulation results.

| Stream Parameters | 129 °C | | 130 °C | | 131 °C | |
|--------------------------------|--------|---------|--------|---------|--------|---------|
| | T (°C) | P (MPa) | T (°C) | P (MPa) | T (°C) | P (MPa) |
| ORC Working Fluid at Point 1 | 30 | 0.17 | 30 | 0.18 | 30 | 0.18 |
| ORC Working Fluid at Point 2 | 31.06 | 2 | 31.06 | 2 | 31.06 | 2 |
| ORC Working Fluid at Point 3 | 129 | 2 | 130 | 2 | 131 | 2 |
| ORC Working Fluid at Point 4 | 60 | 0.12 | 60 | 0.12 | 60.02 | 0.1 |
| Water (Inlet) | 15 | 0.5 | 15 | 0.5 | 15 | 0.5 |
| Water (Outlet) | 54.87 | 0.5 | 54.89 | 0.5 | 53.33 | 0.5 |
| Heat Transmitting Oil (Inlet) | 163 | 0.35 | 163.5 | 0.35 | 164.5 | 0.35 |
| Heat Transmitting Oil (Outlet) | 84.5 | 0.35 | 84.5 | 0.35 | 84.5 | 0.35 |

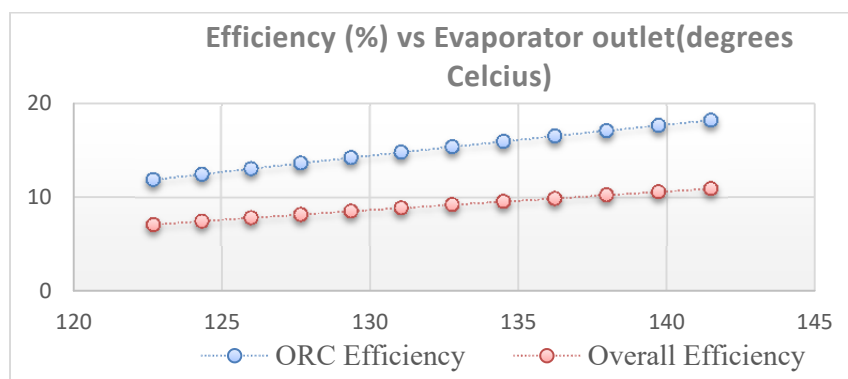


Figure 4. Variation of evaporator outlet temperature (x-axis) vs efficiencies (y-axis).

6. Economic analysis

Various methods are used for economic evaluation of energy generating systems. The most common ones are: Savings to Investment Ratio (SIR), Levelized Cost of Electricity (LCOE), Internal Rate of Return (IRR), Depreciated Payback Period (DPP), and Net Present Value (NPV). The DPP and LCOE are used in this study.

The DPP determines the number of time period(s) that is needed until an investor fully recovers the initial cost of investment [12]. It is given by:

$$DPP = \ln\left(1 - \frac{kC_0}{F_n}\right) / \ln(1 + k) \quad (11)$$

F_n -the net cash flow in the year n (assumed to be constant during the lifetime period)

$F_n = B_n - C_n$, B_n is the benefit (inflows) for year n , C_n is the outflows for year n , C_0 the initial investment, k is the interest rate [13].

The LCOE is also known as cost of generating electricity from a specific system. It includes all costs needed for the generation of electricity, initial investment, operation and maintenance (O&M), cost of fuel, insurance etc. It shows the minimum cost at which electricity should be sold for the project to break even. It is expressed as;

$$LEC = \sum_{n=0}^N \frac{C_n + O\&M + F_n}{(1+K)^n} / \ln \sum_{n=1}^N \frac{E_n}{(1+K)^n} \quad (12)$$

Based on the market survey, catalogues and offers from heating, ventilation and air conditioning components suppliers (list) Beijing, China; cost estimation of a 2kW ORC system was estimated and displayed in Table 5.

Table 5. Components estimated cost.

| Items | Cost (\$) | % |
|-------------------------------------|-----------|-------|
| Equipment | | |
| PV | 7,500 | 34.2% |
| O-Tank | 450 | 2.1% |
| Heat Exchanger | 3,000 | 13.7% |
| Expander | 2,500 | 11.4% |
| Condenser | 3,000 | 13.7% |
| Water pump | 500 | 2.3% |
| R245fa | 800 | 3.6% |
| Therminol 55 oil | 700 | 3.2% |
| Piping system | 700 | 3.2% |
| Control system | 900 | 4.1% |
| Fluid pump | 1,500 | 6.8% |
| Miscellaneous | 400 | 1.8% |
| Total Equipment Cost(TEC) | 21,950 | 100% |
| Labor cost (10% TEC) | 2195 | - |
| Total Installed Cost(TIC) | 24,145 | - |
| Specific installed cost | 12,073 | - |
| Annual cost | | |
| Operation and Maintenance (7.5%TIC) | 1810 | - |
| Insurance (0.5%TIC) | 121 | - |
| Total annual cost | 1931 | |

The following assumptions have been considered the lifetime period is 20years, load factor of 85% (310days), the system degradation rate is approximately 5%, inflation rate in electricity price is 4%, interest rate 5% and the general inflation is 7%.

The cost estimation was carried out for 2kW ORC, the total installed cost added up to \$ 21,950 with specific installed cost of \$12,073 assuming that the operation and maintenance cost is 7.5% of the total installed cost and 0.5% for insurance, total cost is approximately 1,931\$/year.

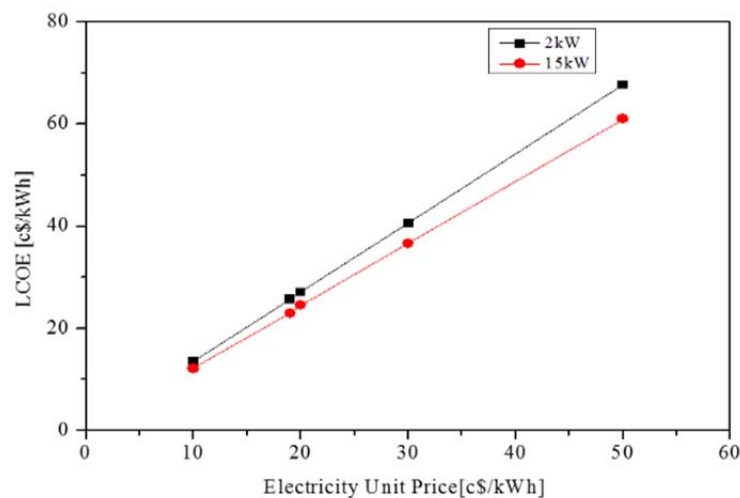


Figure 5. Variation of LCOE with electricity unit.

Figure 5 shows the variation of the Levelized electricity cost for the 2kW and 15kW system, the value of LCOE decreases as the size of the system increases, it can be predicted that medium and large size PV-ORC system could produce electricity at a cost much lower, below 10 c\$/kWh. The DPP is about 10 years for electricity price of 10 c\$/kWh for 2kW system and 6 years for 15kW ORC system. Comparing with the cost of electricity in Kenya, the results show that 2kW system and above will be economically viable for the weather conditions considered in this paper.

The cost per kWh unit is Ksh 181.77 \approx \$1.8 as at March, 2018 (source; <https://calculator.co.ke/kenya-power-postpaid-bill-calculator>). Comparing cost of electricity in Kenya the project will not only be viable but has good prospects given that there is recovery of waste heat energy.

7. Conclusions

The economics and thermoeconomics analysis of low cost ORC incorporated in a combined solar photovoltaic cum thermal plant was carried out using Aspen plus simulation software, based on the weather conditions of Thika. The payback period for the solar ORC system for both 2kW and 15kW was below the life cycle of the system which indicates that the system is feasible and suitable for investment purposes. The PV-ORC system has some benefits which include: hot water as a byproduct (55°C) at no extra charge, low labor cost and possibility of accumulating heat for delayed use through the use of thermal storage tank. The ORC is a promising technology for waste-heat recovery applications in areas without (or with high cost) access to the national grid electricity supply. The PV-ORC system which uses solar energy if implemented can assist in developing sustainability and serve to sustain the lives of millions of underprivileged people living in rural areas in Kenya hence assisting in attaining the millennium development goal and Kenya's vision 2030.

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