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Photovoltaic Thermal (PV/T) Water Heating System for Energy Efficiency Optimization

Margaret Wanjiku
Mechatronic Engineering
Dedan Kimathi University of Technology
Nyeri, Kenya
maggiemwas@gmail.com

Charles Kagiri
Mechatronic Engineering
Dedan Kimathi University of Technology
Nyeri, Kenya
charles.kagiri@dkut.ac.ke

Francis Maina
Mechatronic Engineering
Dedan Kimathi University of Technology
Nyeri, Kenya
maina.francis@dkut.ac.ke

Titus Mulembo
Mechatronic Engineering
Dedan Kimathi University of Technology
Nyeri, Kenya
titus.mulembo@dkut.ac.ke

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***Abstract*—Current trends in climate change are an undeniable threat to clean, affordable and renewable energy access. One main cause is the emission of greenhouse gasses from thermal power plants. According to research on the Kenya household energy consumption, water heating for cooking, cleaning, and bathing takes the highest percentage of energy consumed in the home. To reduce the high percentage household consumption from water heating, a photovoltaic thermal (PV/T) water heating system for energy efficiency optimization was designed. The system is a solar PV/T integration with the heat pump (HP) and main grid, with an aim of maximizing use of generated renewable energy instead of the metered power. An optimization using the OPTI toolbox in MATLAB was done with the objective to optimize energy usage and minimize the metered cost. For a sampling period of $t_s = 15min$ chosen over a 24-h horizon, an energy saving efficiency of $r = 27.52\%$ (covariance) is achieved.**

***Index Terms*—Optimal control, solar thermal power, photovoltaic-thermal**

I. INTRODUCTION

Efficient, environment friendly, sustainable, and cost-effective energy systems have become a necessity with the increasing energy demand [1]. Domestic hot water demand is one of the greatest consumers of energy in Kenya [5], [6]. Thermal energy power plants are commonly used providing an average of 32% of the energy sector in the country [4]. However, thermal power harvesting results in increased cost and adverse environmental impacts which lead to global warming and health issues [2]. This has led to an urgent need for a shift from reliance on conventional energy to renewable energy systems. On the one hand,the renewable sources still pose a challenge of intermittency, unpredictability and hence a mismatch between supply and demand thus creating the need for co-generation [2], [3]. On the other hand, co-generation systems have been found not to follow thermal demands. This has led to a growing need for efficient technologies that reduce the consumption of energy from the grid while utilizing the renewable resources available. Photovoltaic systems offer an efficient method of converting solar radiation to electricity and are widely used as viable choices instead of using the power grids [13]. However, the performance of PV cells decline with increase in temperature and only 10-20% of solar radiation is converted into electricity [13], [14].The remainder is diffused as heat resulting in degradation and power reduction . The challenge can be dealt with by extracting the excess heat which can be utilized to meet hot water demand while increasing the electricity output [10], [11]. This study focuses on the use of photovoltaic-thermal (PVT) systems which integrate the PV module and solar thermal collectors (ST). The PVT has drawn consideration in recent years due to its increased electrical, thermal output capabilities, and reduction of the total collector area. [7], [8]. Heat pumps have also become popular as devices for minimizing energy consumption for provision of hot water [12]. The heat pump (HP) output depends on its coefficient of performance (COP) and works on the principle of refrigerant cycle. It converts one unit of electrical energy to produce three units of thermal energy and therefore, more energy efficient compared to use of conventional electric resistance heaters [9].

In this context, the PVT system is integrated with the heat pump to produce hot water for domestic application. The electricity output by the PVT is used to run the heat pump. The feasibility of the system is examined and its performance such as electricity generation and and energy saving efficiency evaluated on real real time weather conditions.

II. SYSTEM MODEL AND FORMULATION

A. Schematic Layout

Figure 1 shows the proposed diagram of the domestic water heating system proposed for this study. It comprises

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M.W. is a masters student for Advanced Manufacturing and Automation Engineering (AMAE) in the department of Mechatronic Engineering of DKUT.

C.M. and T.M. are senior lecturers in the department of Mechatronic Engineering of DKUT.

F.I. is a tutorial fellow in the department of Mechatronic Engineering of DKUT.

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a photovoltaic/thermal (PV/T), grid and a solar assisted heat pump (PVT-SAHP). The heating devices are powered by the photovoltaic thermal P_{pvt} while the grid P_g acts as a back up when the solar energy is insufficient. The PV/T supplies hot water to the residential house when there is demand and there renewable energy is available. The electricity output from the PV/T is used to run the HP which relies on the grid when the electricity supply is not enough. The HP supplies hot water when the renewable energy is not available.

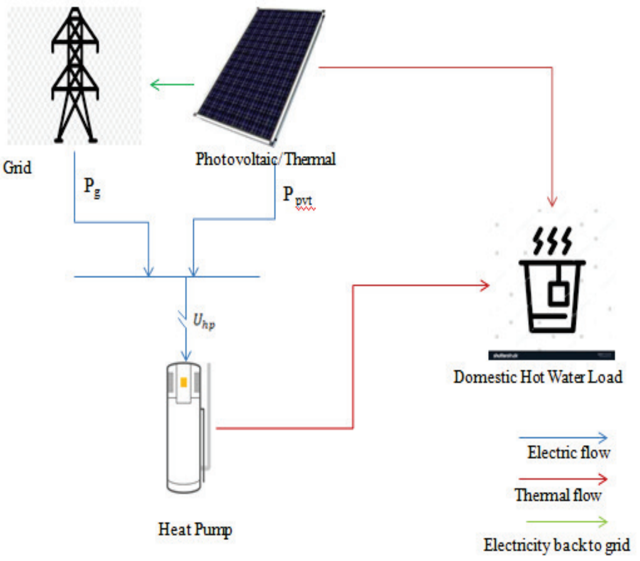

Fig. 1. Integrated PV/T Water Heating System

The integration allows cooling of the PV/T hence increasing its energy conversion efficiency while the HP benefits from higher evaporation temperature provided by the PV/T.

1) Photovoltaic/Thermal energy: The PVT has thermal and electricity output. Thermal energy produced covers the building energy demand while the electricity powers the HP reducing the primary energy consumption. The performance of the PVT is based on electric efficiency (η_{el}) and thermal efficiency (η_{th}). The overall energy efficiency (η_{l}) is the sum of the electric and thermal output. Electric efficiency is comprised of a fraction of incident solar radiation converted to electricity and is given by;

$$\eta_{\mathrm{el}} = \frac{P_{\mathrm{el}}}{G_{\mathrm{t}} A_{\mathrm{c}}} \tag{1}$$

Where P_{el} is the electric power generated by the module and G_t is the total solar irradiance hitting the module and A_c is the area of the collector exposed to the sun (m^2). Thermal efficiency is calculated as;

$$\eta_{\mathrm{th}} = \frac{Q_{\mathrm{th}}}{G_{\mathrm{t}} A_{\mathrm{c}}} = \frac{\rho \dot{V} C (T_{\mathrm{out}} - T_{\mathrm{in}})}{G_{\mathrm{t}} A_{\mathrm{C}}} \tag{2}$$

Where $\dot{Q}_{\mathrm{th}}$ is the fraction of solar irradiance recovered by heat transfer fluid, ρ is the heat transfer fluid density, $\dot{V}$ is the volumetric flow rate and c is the specific heat transfer of the fluid, and T_{out} and T_{in} are thermal power of the heat transfer at the outlet and inlet of the collector respectively.

2) Photovoltaic Thermal Solar Assisted Heat Pump: The output hot water from the system is used to provide domestic hot water. The water tank of the PVT acts as an energy source of the HP while the condenser water tank acts as the energy sink. The performance of the heat pump is evaluated as by the coefficient of performance (COP) which is calculated as;

$$COP_{\mathrm{HP}} = \frac{\dot{Q}_{\mathrm{C}}}{\dot{W}_{\mathrm{K}}} \tag{3}$$

Where $\dot{Q}_{\mathrm{C}}$ the heat is output of the condenser and $\dot{W}_{\mathrm{K}}$ is the compressor work. The combined system gives the coefficient of thermal and electrical performance ($COP_{PVT/HP}$) as;

$$COP_{\mathrm{PVT/HP}} = \frac{\dot{Q}_{\mathrm{C}} + \dot{E}_{\mathrm{elec}}}{\dot{W}_{\mathrm{K}}} \tag{4}$$

Where $\dot{E}_{\mathrm{elec}}$ is the electricity production from the PV.

3) Grid energy: The grid supplies power to hot water devices and the HP when solar energy is insufficient. It also accepts excess power from the PVT. The model uses a standard electrified tariff. The hourly power balance to meet hot water demand is shown in the following equation;

$$P_{\mathrm{g}}(t) + P_{\mathrm{pvt}}(t) = P_{\mathrm{hp}}(t) \tag{5}$$

Where $P_{hp}$is the power rating (kW) of the HP.

B. Optimization Problem

The aim is to minimize the cost of grid power consumed to meet the hot water demand and operate the HP. A 24-h evaluation period will be considered with operating cycle from 0 to 24 with a sampling period of t_s=15. The objective function is expressed as;

$$J = \omega_1 \Sigma_{j=1}^{N} t_{\mathrm{s}} \rho_{\mathrm{e}}(j) P_{\mathrm{g}}(j) + \omega_2 \Sigma_{j=1}^{N} t_{\mathrm{s}} P_{\mathrm{hp}} U_{\mathrm{hp}}(j) \tag{6}$$

Where; ω is the weighting factor, ρ_{e} is the price of electricity, and j is the sampling interval and $U_{\mathrm{hp}}$is the status of the PVT-SAHP switch. The first term aims to minimize the cost of the grid power used by hot water devices while the second targets to minimize the operation of the heat pump when there is low demand.

Power balance of the system represents the equality constraints;

$$P_{\mathrm{g}}(j) + P_{\mathrm{pvt}}(j) = P_{\mathrm{hp}}(j) \tag{7}$$

For every sampling interval j, the power demand from domestic load and domestic hot devices is met by the power from the PV/T and the grid. The state variables are, the temperature of water from the HP and PV/T. Minimum and maximum temperatures are set for every sampling interval such that;

$$\begin{aligned} T_{pvt}^{min} &\leq T_{\mathrm{pvt}}(j) \leq T^{\mathrm{max}} \\ T_{hp}^{min} &\leq T_{\mathrm{hp}}(j) \leq T^{\mathrm{max}} \end{aligned} \tag{8}$$

The grid provides and accepts the power back, hence, the boundaries are,

$$0 \leq P_{\text{g}}(j) \leq \infty \tag{9}$$

The status of the HP can either be on or off hence 0 or 1;

$$U_{\text{up}}(j) \in 0, 1 \tag{10}$$

The syntax used for solving the objective function are;

$$min_{\text{x}} f^T X \tag{11}$$

Subject to;

$$AX \leq b \text{ (Linear inequality constraint)}$$
$$A_{\text{eq}} X = b_{\text{eq}} \text{ (Linear equality constraint)}$$
$$L_{\text{B}} \leq X \leq U_{\text{B}} \text{ (Lower and upper boundary)}$$

A case study was conducted in a house in Embu, Mbeere region Kenya, having a hot water demand profile as shown in 2.

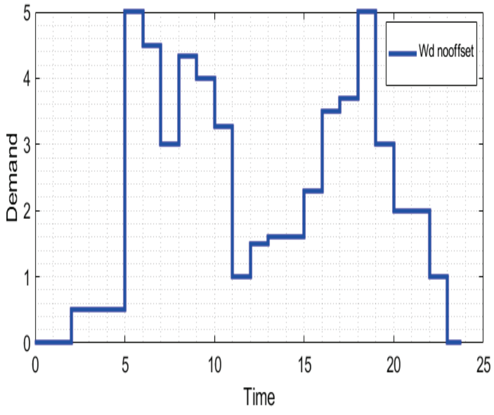

Fig. 2. Residential hot water demand

III. RESULTS AND DISCUSSION

The problem is solved in MATLAB using the OPTI toolbox. The sampling period is t_s=15min chosen over a 24-h horizon, hence the number of samples N=96. The tariff used is standard throughout the day at 20 US cents per kWh. Figure 3 shows most energy is consumed during the day when the hot water demand is high. The HP remains on from 0600hrs time to 1800hrs time in order to meet the demand. The collector gives a thermal output for 5 hours from 1000hrs to 1500hrs as shown in figure 4. The thermal output is used to offset the hot water demand in the house. When there is no demand in the house, the hot water from the PV/T is stored in a reservoir to offset later demand. During the day, the energy from the PVT offsets both the hot water demand and the energy from the grid.

When there is demand and the water from the PV/T reservoir is not sufficient, the demand is met by the hot water from the HP.

Figure 5 shows the optimal consumption from the grid. The grid is used between 0600hrs and 1800hrs when the demand is high. The demand between 1800hrs and 0600hrs is met by the hot water stored in the heat pump and PVT reservoir.

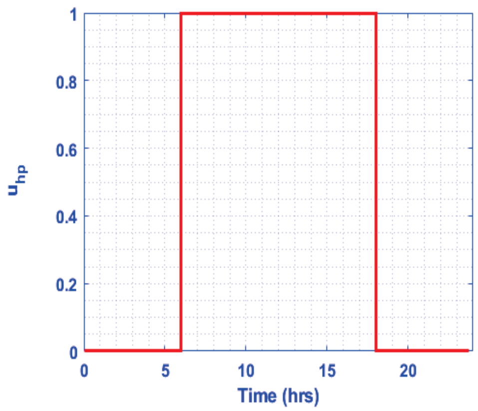

Fig. 3. Heat pump switch status

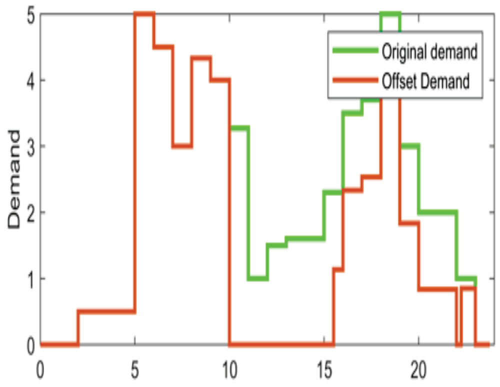

Fig. 4. Original hot water demand and demand offset by PV/T

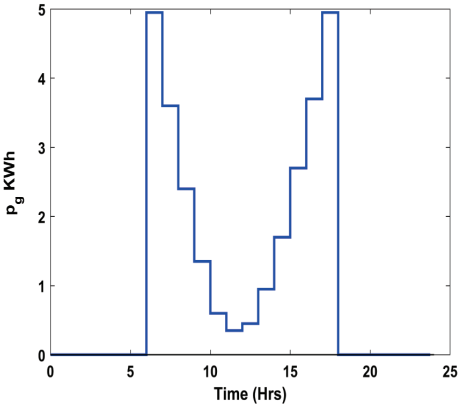

Fig. 5. Grid power demand against the hourly demand from the PV/T

IV. CONCLUSION

This model provides two methods of minimizing the energy cost of the grid. One is by providing direct hot water from the PV/T to meet the household demand while in the other; the PV/T provides electricity used to run the heat pump. The excess electricity can be fed back to the grid to earn incentives to the consumer in countries where this is applicable. The offset demand results in energy saving cost of $r = 27.52\%$ (covariance between the original demand and the offset demand).

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