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Optimal Energy Management of Grid-Connected Solar-Heat Pump Hybrid Water Heating System

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ABSTRACT

This paper presents an optimal energy control strategy for hybrid solar thermal/heat pump water heaters to address the issue of energy conservation commonly associated with conventional water heaters in residential applications. The pervasive use of fossil-fuel-based water heating technology incurs significant energy costs and contributes to the climate crisis. These have sparked a lot of interest in using renewable technology such as solar water heaters (SWHs). Amidst this, solar radiation intermittent and low efficiency due to PV cell temperature rise have been identified as a limitation to using SWHs. One potential solution to these issues is to explore hybrid technology, which would replace conventional heating technology with a more energy-efficient hybrid solar/heat pump water heater. The main objective of the controller is to reduce the electricity cost by optimizing the operation of the heat pump water heater. A medium-density family in the southwest of Nigeria is selected for the study. The mathematical model was formulated based on the energy balance equations of the sub-system components and then discretized using the Euler forward method. Furthermore, a cost optimization problem with continuous and binary control variables was developed, resulting in a mixed integer problem. This optimization problem was solved using the OPTI toolbox's mixed integer nonlinear programming (MINLP) optimization solver and the solving constraint integer programs (SCIP) algorithm. Simulations were run in MATLAB, and the results show that the optimal control (OC) has a potential energy savings of 61.14% and a cost savings of approximately 70.83% compared to the baseline model. Better utilization of the hybrid system with the OC strategy saves 45.4% more energy than conventional water heaters.

Index Terms—Energy management, grid-connected, hybrid energy system, objective function, optimal control

I. INTRODUCTION

Energy conservation is a major concern in residential buildings, particularly in developing nations such as Nigeria. As we strive to limit our carbon footprint and embrace sustainable practices, it is becoming increasingly important to address energy conservation in these areas. Promoting energy conservation benefits the environment and contributes to developing a sustainable future. Hence, renewable energy integration has recently been a priority in buildings for various reasons. One key area of interest is domestic water heating applications due to their substantial energy consumption and costs. Approximately 40% of energy is consumed in the sector globally [1–3]. For instance, Nigeria's energy production has declined dramatically due to excessive energy demand, resulting in a power crisis and grid load-shedding. Furthermore, studies [4–8] have shown that the increasing use of inefficient electric water heating technology contributes considerably to excessive electrical consumption, resulting in energy price increases. However, researchers actively focus on numerous strategies to cut energy use and costs associated with domestic hot water. On-site grid-connected hybrid solar/heat pump water heating systems offer a viable long-term solution to the problem of thermal energy consumption in residential buildings. To address the conventional energy source reliance issues and minimize energy costs, this hybrid system combined a solar thermal collector with heat pump heating technology. To efficiently minimize energy consumption and save costs, the operation of the proposed hybrid system must be optimized.

A. Literature Review

Numerous studies on hybrid renewable energy systems that combine two or more primary energy technologies for water heating have been conducted, including PV-heat pumps

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connected to a grid [9], solar-electric water heaters [10], wind-PV systems connected to the grid [8], PV-fuel cell-battery system tied to the grid [11], PV-heat pump [12], PV-heat pump integrated systems tied to the grid energy [13, 14], PV-wind-electric water heating systems powered to grid system [15], PV/T-wind-electric water heating system connected to the grid [16], PV-battery-diesel-heat pump integrated systems connected to the grid [17] and, PV-heat pump systems connected to the grid [18]. Researchers have tried optimizing various hybrid water heating configurations to find an optimal cost solution for the grid energy cost problem. Metaheuristic optimization techniques such as genetic algorithms (GA) and particle swarm optimization (PSO) have gained a lot of interest over the last decade. Hybrid optimization (HO) is becoming increasingly common in water heating applications. HO is intended to compensate for the limitations of single meta-heuristic method. In [19, 10], the optimal grid-tied solar-electric hybrid heating systems that minimize the energy cost in residential buildings are presented. The technology uses solar to compensate for energy shortfalls, saving approximately 44% of energy costs. Sichilalu et al [20], presented an optimal grid-connected PV-fuel cell-wind hybrid system, with the objective function of prioritizing energy cost reduction and fuel cell output maximization. This work accounts for cost and energy savings through optimal control (OC). Chen et al. [21], proposed an optimal grid-tied PV-wind electric hybrid water heating system in a residential building. The hybrid technology employs PV and wind to meet the thermal load energy needs. In this study, a conventional ON/OFF controller is used to optimize the hybrid model. Okubanjo et al. [22], presented a techno-economic study of hybrid renewable systems to address energy conservation issues in residential buildings. The evaluation demonstrates that the hybrid system's potential not only cuts costs and energy consumption but also contributes to climate change mitigation. In [23], optimal grid-connected hybrid renewable water heating systems were developed. The model seeks to lower electricity costs by using an optimal controller. The optimized model in this study saves 114.10 kWh of daily energy, resulting in a 32% cost reduction. Li et al. [24] presented an optimal PV-battery-diesel hybrid systems linked to the grid for minimizing grid energy cost. When solar energy is insufficient, the model relies on batteries and diesel backup. The model used a hybrid control method to solve the cost optimization problem [25], and presented an optimal controller for PV-battery systems, while [26] proposed an optimal control strategy based on a genetic algorithm [20], proposed a system that combines solar panels, fuel cells, and wind turbines with the grid to meet the heating needs of households. Their main objective is to decrease grid energy expenses while upholding thermal output. A similar study presented by the author in [27] integrated a battery into the previous study to compensate for energy deficits in the absence of solar power output. This work established grid energy cost as another objective function that must be optimized. [28], presented an efficient hybrid energy management system for electric vehicles based on a DC Microgrid. The model seeks to maintain a consistent power equilibrium within the Microgrid while extending the lifespan of the storage devices. The proposed hybrid control strategy has potential energy savings of 7.78% than the particle swarm optimization. An adaptive control strategy is proposed in [29] for power quality enhancement in distribution systems. A novel adaptive linear neutral technique was developed and compared with the existing algorithms. The proposed optimal model exhibits superior outcomes than the compared algorithm. In addition, an adaptive control optimization algorithm is proposed in [30], to tackle the declining power quality issue in distribution systems. The integration of feed-forward elements in PV systems offsets shunt losses and efficiently manages power distribution between grid energy and load.

B. Study Gap and Motivation

The previous studies on optimal control energy management focused mainly on hybrid systems that integrate solar, wind, fuel-cell, and other renewable energy sources with either electric or heat pump water heaters. However, research on the optimal operation of hybrid solar thermal collector/ heap pump water heating systems is rarely reported in Nigeria. This is an opportunity to explore hybrid technology that combines solar thermal collectors, heat pumps, and the grid system in addressing the problem of energy consumption and compensating for solar vulnerability in solar water heaters through the grid energy at a time-of-use pricing strategy.

Another motivation for this study is there is no study on the use of optimal control for energy demand side management, particularly in Nigeria that due with energy cost optimization in residential water heating applications. Therefore, this study seeks to promote the use of hybrid technology as a potential solution that could significantly advance Africa's sustainable development goals, particularly in Nigeria, while also addressing the country's energy crisis.

C. Contributions

The following are the novel contributions of this study:

1. To highlight the potential of using an optimal control energy management scheme for hybrid solar/heat pump water heaters to achieve significant energy and cost savings.
2. To develop a mathematical model of a hybrid model.
3. To develop an optimal control strategy for a hybrid solar/heat pump water heating system.
4. To highlight the potential benefits of the proposed OC approach over conventional ON/OFF controllers.
5. To validate the proposed hybrid model, MATLAB results were compared to the baseline controller.

The novelty of this study is to design a new hybrid renewable water heating system that addresses cost optimization problems in medium-density homes. In addition, an optimal control strategy using mixed integer nonlinear programming (MINLP) was developed to address cost issues in contrast to traditional control approaches like ON/OFF, bang-bang, or proportional-integral-derivative (PID) controllers. Furthermore, a new mathematical framework was developed for hybrid solar thermal collector-grid connected heat pump water heaters. The efficient system is achieved by combining solar thermal collector-grid-heat pump water heaters with an optimal control strategy that reduces grid energy costs. In addition, the proposed model has a shorter discounted payback period with a significant OC benefit as revenue than baseline HPWHs.

II. SYSTEM MODEL

The proposed hybrid model is presented in Fig. 1. It is made up of three parts: the grid system (GS), the heat pump (HP), and the solar thermal collector (STC). The thermal load requirements are met by operating the hybrid system. Hence, the mathematical models of the system components and their parameters are presented as follows:

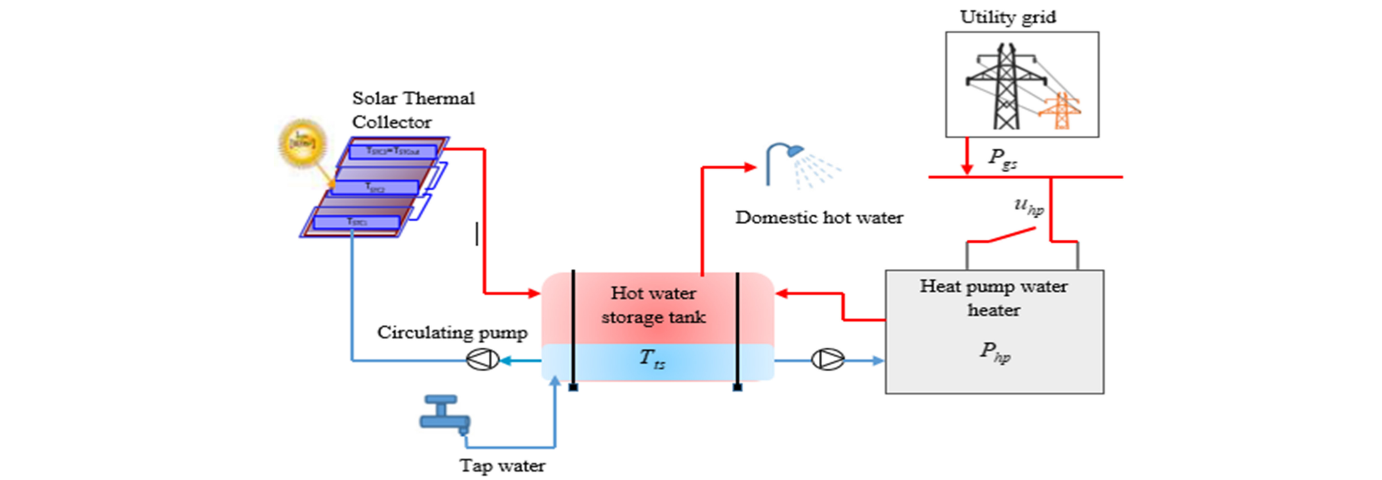

Fig 1. Proposed mode

A. Utility grid system (GS) model

The power balance model in meeting hot water demand is formulated as:

$$P_{hp}u_{hp}(t) - P_{gs}(t) = P_{sc}(t) \quad (1)$$

The pricing mechanism (ToU) is based on the energy supply availability and the price of electricity per hour is formulated [18] as

$$P_{he}(t) = \begin{cases} P_{of} = 51.22N / \text{KWh} \quad \text{if} \quad t \in |0,5| \cup |8,19| \cup |22,24| \\ P_{ph} = 51.22N / \text{KWh} \quad \text{if} \quad t \in |5,8| \cup |19,22| \end{cases} \quad (2)$$

where P_{he} represents the hourly price of electricity for residential households that use electricity for a minimum of 20 hours daily. t denotes the hourly time of day, NR is the Nigerian dollars, Naira. P_{of} denotes off-peak, and P_{dh} signifies the peak hour. u_{hp} represents the status of the HPWH switch (ON or OFF). The selected energy tariff represents the energy charges for customers in band B for 2021.

B. Heat Pump (HP) model

The required input power to satisfy the HPWH demand is given [3] by

$$H_{hp}(t) = P_{hp}u_{hp}CP_{hp}(t) \quad (3)$$

where H_{hp} denotes the HPWH heating capacity and CP_{hp} represents the coefficient of performance of HPWH.

C. Solar Collector (SC) model

The dynamics of the hybrid model are based on standby loss from heat storage, collector gain, heat gain, and hot water heat losses. The overall heat response of the tank's water is thus described by first-order equations, as proposed in, [18] as:

$$m_{ts}C_w \frac{dT_{ts}}{dt} = H_{SC} + H_{hp} - H_S - H_{WD} \quad (4)$$

$$\frac{dT_{ts}}{dt} = -\theta T_{ts}(t) + \varphi u_{hp}(t) + \lambda(t) \quad (5)$$

where,

$$\theta = \left(\frac{U_{ts}A_{ts}}{C_w} + W_d^h(t)\right)m_{ts}^{-1} \quad (6)$$

$$\varphi = P_{hp}CP_{hp}\left(m_{ts}C_w\right)^{-1} \quad (7)$$

$$\lambda = \frac{\frac{m_{SC}}{m_{ts}}A_{SC}I_{SC}(\tau\alpha)_{SC}}{m_{SC}C_w + A_{SC}F_R U_L} + U_{ts}A_{ts}\left(m_{ts}C_w\right)^{-1} + W_d^h T_{ci}(t)\left(m_{ts}\right)^{-1} \quad (8)$$

The discrete representation of Eq. (5) is given as:

$$T_{ts}(i+1) = (1 - t_s\theta(i))T_{ts}(i) + t_s\phi u_{hp}(i) + t_s\lambda(i) \quad (9)$$

After recursive manipulation, the dynamic the storage tank's hot water temperature can be modelled as in Eq. (10).

$$T_{ts}(i+1) = T_{ts}(0)\prod_{j=0}^{i} 1 - t_s\theta(j) + \phi t_s \sum_{j=0}^{i} u_{hp}(j) \prod_{k=j+1}^{i} 1 - t_s\theta(k) + t_s \sum_{j=0}^{i} \lambda(j) \prod_{k=j+1}^{i} 1 - t_s\theta(k) \quad (10)$$

where T_{ts} (0) represents the initial water temperature and T_{ts} (i) denotes i[th] water temperature, t_s is sampling time, θ and φ are function while λ denotes disturbance variable.

D. Objective function model

The model's objective is to reduce the cost of electricity used to run HPWH in the absence of solar power. The model objective function is expressed in discrete time for a 24-horizon as follows:

$$J = \omega_{hs} \sum_{n=1}^{24} t_s P_{he}(i) P_{gd}(i) u_{hp}(i) \quad (11)$$

where t_s is the sampling time, i denotes the sampling interval, $i,\ldots,$ 24, and ω_{hs} represents the weighting factor for the hybrid system.

E. Model Constraints

The following operational constraints apply to the proposed hybrid system's objective function:

$$T_{ts}^{\min}(i) = T_{ts}(i+1) \le T_{ts}(0)\prod_{j=0}^{i}(1-t_s\theta(j))$$

$$+\phi t_s \sum_{j=0}^{i} u_{hp}(j) \prod_{k=j+1}^{i}(1-t_s\theta(k)) \tag{12}$$

$$+t_s \sum_{j=0}^{i} \lambda(j) \prod_{k=j+1}^{i}(1-t_s\theta(k)) \le T_{ts}^{\max}$$

$$u_{hp}(i) \in \{0,1\} \tag{13}$$

$$T_{ts}^{min(i)_{ts}(i)_{ts}^{max}} \tag{14}$$

$$0 \le P_{sc}(i) \le P_{sc}^{max} \tag{15}$$

$$-\infty \le P_g(i) \le \infty \tag{16}$$

F. Optimization solver

The optimization model contains continuous, binary, linear, and nonlinear constraints, resulting in a mixed integer nonlinear problem. The MINLP problem is solved with the MATLAB OPTI toolbox. The generic expression of the linear inequality is thus derived by modifying the optimization constraints with the general MINLP algorithm solver as follows:

$$AX \le b \tag{17}$$

where vector ***X*** is a column matrix that composed of switch u_{hp} (i) and the grid power grid P_{gd} (i) and is written as:

$$\boldsymbol{X} = \left[\boldsymbol{u_{hp}}(0) \quad \cdots \quad \boldsymbol{u_{hp}}(N-1), \boldsymbol{P_{gd}}(0) \quad \boldsymbol{P_{gd}}(N-1)\right]_{2N\times 1} \tag{18}$$

Therefore, the special matrices **A** and vector ***b*** in equation (17) are formulated as:

$$\begin{bmatrix} A_1 \\ -A_1 \end{bmatrix}_{N\times 2N} \left[X\right] = \begin{bmatrix} b_1 \\ b_2 \end{bmatrix}_{N\times 1} \tag{19}$$

Hence, equation (10) is rearranged to yield A_1, b_1 and b_2 as follows:

$$T_{ts}^{min(i)_{ts}(0)\prod_{j=0}^{i}(1-t_s\theta(j))_c \sum_{j=0}^{i} u_{hp}(j)\prod_{k=j+1}^{i}(1-t_s\theta(k))}$$

$$+t_s \sum_{j=0}^{i} \lambda(j) \prod_{k=j+1}^{i}\left(1-t_s\theta(k)\right) \tag{20}$$

$$-\varphi t_s \sum_{j=0}^{i} u_{hp}(j) \prod_{k=j+1}^{i}\left(1-t_s\theta(k)\right) \le -T_{ts}^{min_{ts}(0)\prod_{j=0}^{i}(1-t_s\theta(j))}$$

$$+t_s \sum_{j=0}^{i} \lambda(j) \prod_{k=j+1}^{i}\left(1-t_s\theta(k)\right) \tag{21}$$

Similarly,

$$T_{ts}(0)\prod_{j=0}^{i}\left(1-t_s\theta(j)\right) + \varphi t_c \sum_{j=0}^{i} u_{hp}(j) \prod_{k=j+1}^{i}\left(1-t_s\theta(k)\right)$$

$$+t_s \sum_{j=0}^{i} \lambda(j) \prod_{k=j+1}^{i}\left(1-t_s\theta(k)\right) \le T_{ts}^{max}$$

$$\varphi t_s \sum_{j=0}^{i} u_{hp}(j) \prod_{k=j+1}^{i}\left(1-t_s\theta(k)\right) \le T_{ts}^{max} - T_{ts}(0)\prod_{j=0}^{i}\left(1-t_s\theta(j)\right)$$

$$-t_s \sum_{j=0}^{i} \lambda(j) \prod_{k=j+1}^{i}\left(1-t_s\theta(k)\right) \tag{22}$$

Hence, equations (21) and (22) satisfy the general expression of linear inequality constraints, allowing the matrices A and b to be obtained in matrix form. To simplify and eliminate computation error, the common term $(1 - t_s\theta(k))$ in the equations is replaced with α (i,j,k), to yield Eqs (23 and 24).

$$\varphi t_s \sum_{j=0}^{i} u_{hp}(j) \prod_{k=j+1}^{i} \alpha(j) \le -T_{ts}^{min_{ts}(0)\prod_{j=0}^{i}\alpha(i)}$$

$$+t_s \sum_{j=0}^{i} \lambda(j) \prod_{k=j+1}^{i} \alpha(k) \tag{23}$$

$$\varphi t_s \sum_{j=0}^{i} u_{hp}(j) \prod_{k=j+1}^{i} \alpha(j) \le T_{ts}^{max_{ts}(0)\prod_{j=0}^{i}\alpha(i)}$$

$$+t_s \sum_{j=0}^{i} \lambda(j) \prod_{k=j+1}^{i} \alpha(k) \tag{24}$$

Hence, the element of vector $\boldsymbol{b}_1$ and $\boldsymbol{b}_2$ can be expressed as follows:

$$b_{1,i} = -T_{ts}^{min_{ts}(0)\prod_{j=0}^{i}\alpha(i)_s \sum_{j=0}^{i}(j)\prod_{k=j+1}^{i}\theta(k)} \tag{25}$$

$$b_{2,i} = T_{ts}^{max_{ts}(0)\prod_{j=0}^{i}\alpha(i)_s \sum_{j=0}^{i}\lambda(j)\prod_{k=j+1}^{i}\alpha(k)} \tag{26}$$

$$b_1 = b_{1,1} - b_{1,2} - b_{1,3} \tag{27}$$

where,

$$b_{1,1} = [T_{ts}^{\min} \ldots T_{ts}^{\min}]^T \; N \times 1$$

$$\boldsymbol{b}_{1,2} = \begin{bmatrix} \pm(0) \\ \pm(1)\pm(2) \\ \pm(1)\pm(2)\pm(3) \\ \vdots \\ \pm(\boldsymbol{N})\pm(\boldsymbol{N}-1)\cdots\pm(0) \end{bmatrix}_{\boldsymbol{N}\times 1} \tag{28}$$

$$\boldsymbol{b}_{1,3} = \begin{bmatrix} \boldsymbol{t}_s\text{»}(0) \\ \pm(1)\boldsymbol{t}_s\text{»}(0)+\boldsymbol{t}_s\text{»}(1) \\ \pm(2)\pm(1)\boldsymbol{t}_s\text{»}(0)+\pm(2)\boldsymbol{t}_s\text{»}(1)+\boldsymbol{t}_s\text{»}(2) \\ \vdots \\ \alpha(\boldsymbol{N}-2)\times\cdots\times\alpha(1)\boldsymbol{t}_s\lambda(0)+\alpha(\boldsymbol{N}-2)\times\cdots\times\alpha(2)\boldsymbol{t}_s\lambda(1)+\cdots+\boldsymbol{t}_s\lambda(\boldsymbol{N}-2) \\ \alpha(\boldsymbol{N}-1)\alpha(\boldsymbol{N}-2\times\cdots\pm(2)\boldsymbol{t}_s\text{»}(1))+\alpha(\boldsymbol{N}-1)\boldsymbol{t}_s\times(\boldsymbol{N}-2)+\boldsymbol{t}_s\lambda(\boldsymbol{N}-1) \end{bmatrix}_{\boldsymbol{N}\times 1} \tag{29}$$

The vector deviation of is b_2 the same as b_1 and is written as:

$$b_2 = b_{2,1} - b_{2,2} - b_{2,3} \tag{30}$$

where,

$$b_{2,1} = [T_{ts}^{\min} \ldots T_{ts}^{\min}]^T \; N \times 1 \tag{31}$$

Then, A_1 is a $N \times 2N$ matrix written as:

$$A_1 = \varphi t_s \begin{bmatrix} 1 & 0 & 0 & 0 & \cdots & 0\vdots & 0 & \cdots 0 \\ \alpha(1) & 1 & 0 & 0 & \cdots & 0\vdots & 0 & \cdots 0 \\ \alpha(2)\alpha(1) & \alpha(2) & 1 & 0 & \cdots & 0\vdots & 0 & \cdots 0 \\ \alpha(3)\alpha(2)\alpha(1) & \alpha(2)\alpha(1) & \alpha(2) & 1 & \cdots & \vdots & 0 & \cdots 0 \\ \vdots & \vdots & \vdots & \ddots & 1 & 0\vdots & 0 & \cdots 0 \\ \alpha(N-2)\times\cdots\times\alpha(1) & \alpha(N-2)\times\cdots\times\alpha(2) & \cdots & \cdots & \alpha(1) & 1\vdots & 0 & \cdots 0 \end{bmatrix}$$

G. Case Study

A medium hostel in the southwest of Nigeria is being examined to understand how energy consumption and costs affect domestic water heating in residential buildings. The hostel uses electric-powered HPWH to meet their daily thermal energy needs for bathing. However, this heating technology depends solely on grid energy and is conventionally controlled by ON/OFF thermostats. The digital ON/OFF thermostat serves as a baseline model and is of the same size as the proposed model. The baseline model, however, is not affected by the solar thermal. Table I shows optimal simulation parameters.

III. SIMULATION RESULTS AND DISCUSSION

Fig. 2 and 3 show that, occupants of this medium household rarely use heated water early in the morning and late at night. In this study, January 3 is chosen as a sampled day; however, there is no demand for hot water during the hours of 00:00–04:00, 07:00–18:00, and 22:00–00:00, primarily because occupants are asleep between 00:50 and 22:00–00:00 and are at work or school between 07:00 and 18:00. The optimal hot water temperature in this study is within the range

TABLE I. OPTIMAL SIMULATION PARAMETERS

Parameter		
A_{SC}	Solar thermal collector area	4 m^2
A_{ts}	Storage tank surface area	1.2 m^2
β_{SC}	Solar collector tilt angle	30°C
C_w	Specific capacity of water	4200 J/K°C
m_{SC}	Collector flow rate	0.011 kg
m_{ts}	Storage tank capacity	150 L
F_R	Heat removal factor	0.625
P_{hp}	Rated power of HPWH	6000 W
Q_{hp}	HPWH heat output	1.714 kW
P_G	Ground reflectance	0.2
T_{ts}^{max}	Maximum storage tank temperature	60°C
T_{ts}^{min}	Maximum storage tank temperature	50°C
T_{ts}	Storage tank temperature	55°C
$(\tau\alpha)_{SC}$	Transmittance absorbance product	0.85
U_L	Overall thermal loss coefficient	7.25 W/m^2 °C
	Thermal storage heat loss coefficient	0.35 W/m
ω_{hs}	Hybrid system weighing factor	0.4
CP_{hp}	HP coefficient of performance	3.5

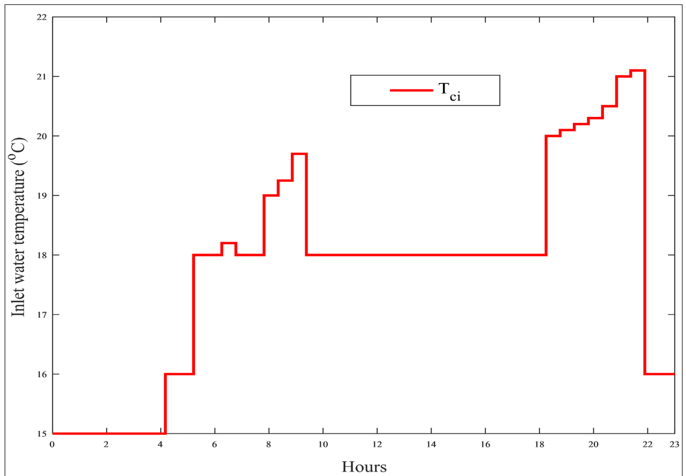

Fig. 2. Hot water flow rate.

of with an ambient air temperature. The storage tank's initial temperature is. The desired temperature, however, varies from individual to individual based on their thermal comfort.

A. Optimal Switching Control Strategy

The optimal control (OC) switch of the HSHP water heater relies on grid usage during low-demand hours to supplement the lack of solar irradiation in meeting hot water demand. As shown in Fig. 4, the HWPW's optimal control switch is turned on between the hours of 00:00 and 02:00 in the morning to preheat the storage tank's water, after which it is kept turned off between 02:00 and 04:00. Thereafter, the OC switch is kept in the off state between of 02:00 and 04:00. The HWPW's optimal control switch activates again after 04:00 a.m. at low energy demand charges to satisfy the expected hot water demand, which begins at 5:00. Furthermore, the OC switch is also turned off at 7:30 to save electricity. The HPWG is deactivated until 16:00 and then activated to warm the water for the evening's high demand as a load-shifting mechanism to minimize costs and energy. It eventually shuts down at 22:00, after switching on for 25 minutes to heat the water since the demand for hot water after this hour diminishes to zero and the tank temperature (T_{ts}) is still above the minimum temperature.

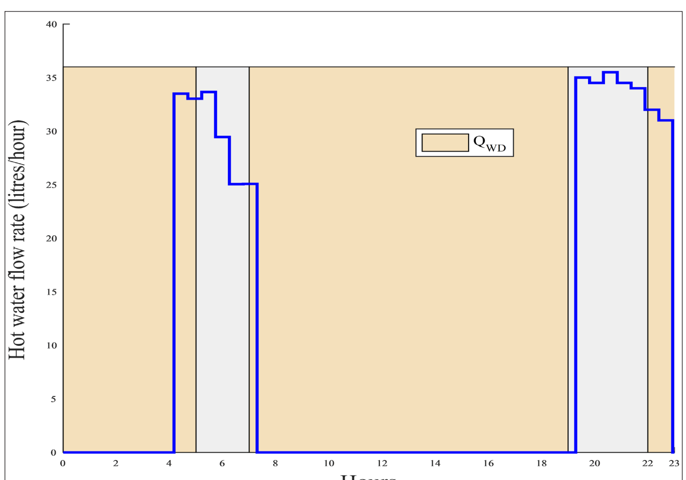

Fig. 3. Hourly inlet cold water.

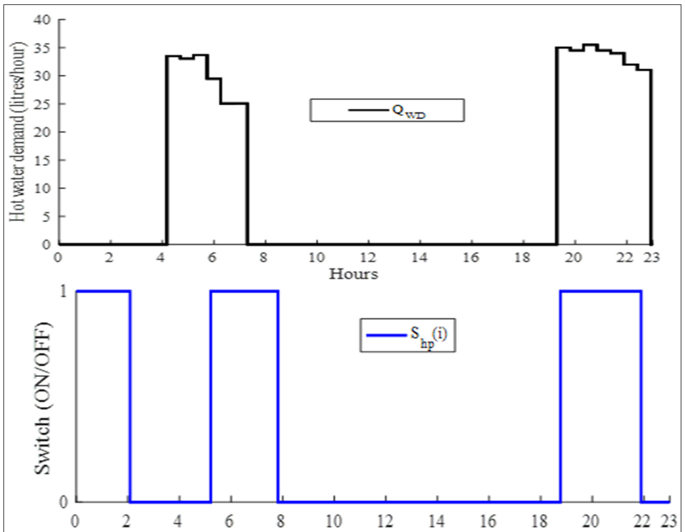

Fig. 4. Optimal Switching Control for HSHP.

B. Optimal and Baseline Control Strategy for the Hybrid System

Fig. 5 shows that the optimal control operates between the period of 00:00 and 02:00 hours; within this period, the initial temperature T_{ts} steadily rises from 55°C to.58.4°C Thereafter, the hot water temperature remains constant between 02:00 and 04:30 with a marginal decrease due to conventional losses and the absence of flow rate. However, the temperature appears to be constant inside this range due to the axis scaling.

Furthermore, the HPWH was turned on again at 05:00 resulting in further storage tank water temperature rise. As a result, T_{ts} rises due to the inlet of cold water and hot water demand resumption. How ever, the temperature decreases after 06:00 due to steady hot water demand, resulting in a further temperature decrease between 08:00 and 19:00 since there was no water heating within these intervals. The OC switch was turned on at 19:00 to preheat the water before the evening hot water demand at electricity charges. In addition, the OC may anticipate the optimal time to turn on the HPWH and provide the end-user with hot water at the desired temperature. Furthermore, the baseline control switch function was simulated to compare the benefits of optimal control switching over baseline switching control. In this case, the baseline control strategy employed a conventional ON/OFF digital thermostat. Fig. 5 shows the comparison result of the baseline and OC strategies. The baseline HPWH's control switch is turned on from midnight until 04:30 to heat water until the T_{ts} attained the maximum temperature. Whether there is a need for hot water or not, the baseline switching control keeps running, using more grid energy. As a result, the hot water demand keeps decreasing T_{ts}. Hence, the baseline control is turned on by 22:00 when it reaches the minimum temperature set point. Since the baseline control has no load-shifting capacity, it runs all day, resulting in significant electricity costs. However, due to the load shifting strategy of the OC, it saves energy and costs.

C. Baseline and Optimal Energy Costs

Fig. 6 and 7 illustrate the daily energy and cost benefits of the baseline and optimal control schemes. The HPWH ON/OFF control switch serves as a baseline energy model that is grid-dependent, and the pricing mechanism is based on the time of use before the deployment of optimal control while the hybrid energy model represents the grid electricity use once OC is adopted.

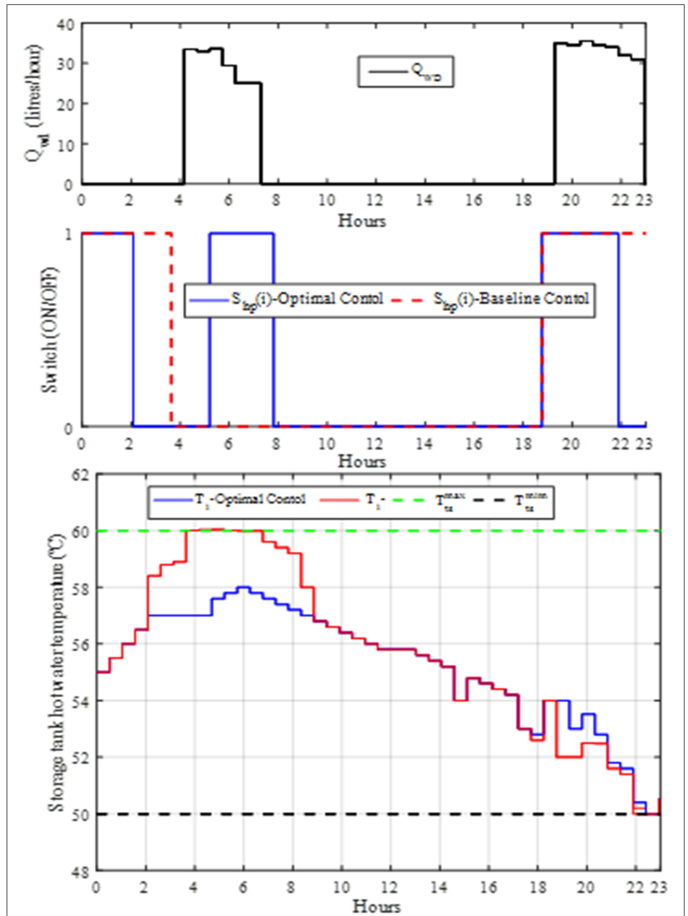

Fig. 5. HSHP scheduling, water demand and storage tank hot temperature

Baseline energy cost is the bill that the hostel occupants pay prior to the introduction of the optimal control strategy. The energy saved is the energy that is not served to the HPWH, which would have been delivered without OC intervention of the hybrid solar/HPWH system.

Table II shows the study's daily energy cost savings for the specified month. According to the data, February has the highest energy and cost savings of 84.00 kWh and 46.10% respectively. The OC strategy benefits the energy user; for instance, in February the OC energy bill was N 179.08/day, representing a cost savings of over 46.10% compared to the baseline energy cost of N 332.93/day. The lowest energy cost savings occurred in November, at 38.89%, as a result of the dry season's higher hot water demand.

IV. ECONOMIC ANALYSIS

Several economic metrics are used in economic assessments to determine the economic viability of any project. These metrics include, among others, the net present worth, lifecycle cost, benefit-to-cost ratio, and return on investment. The net present value and payback duration, on the other hand, are important economic criteria used by investors to rate viable investment proposals. In this study, the NPV and BPP are calculated using a constant inflation rate,

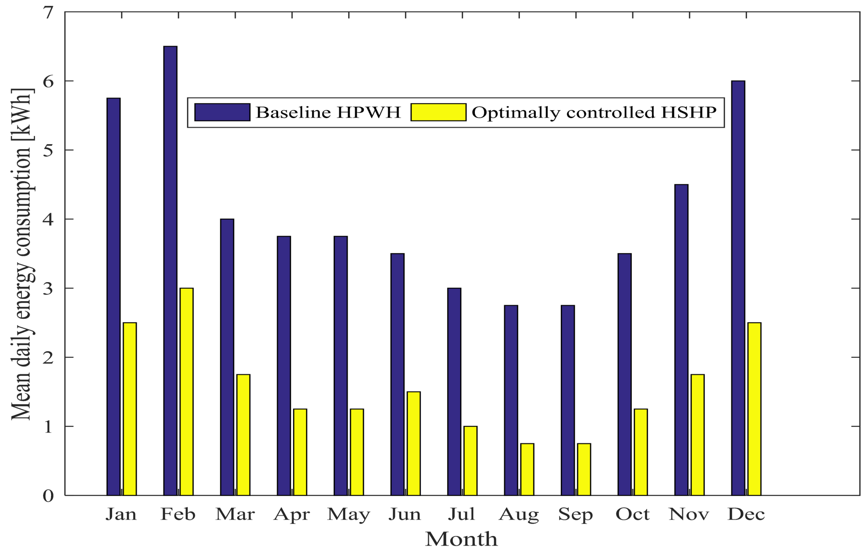

Fig. 6. Monthly average total energy cost (2022)

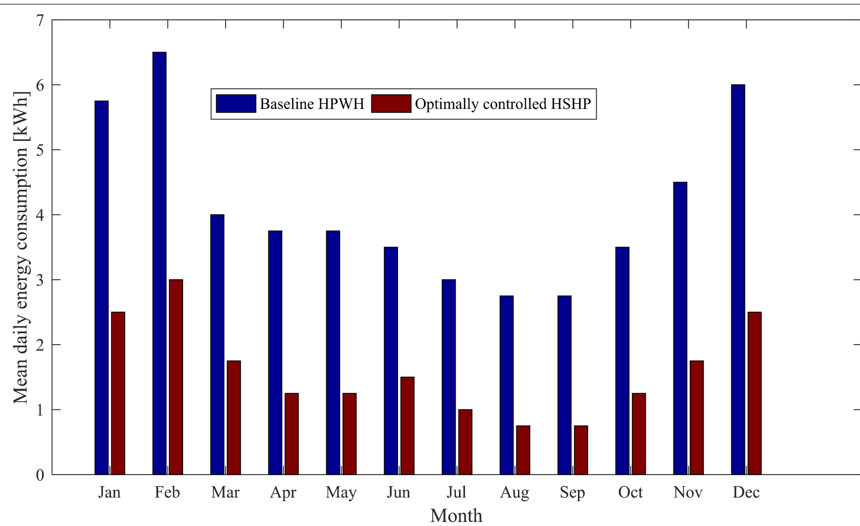

Fig. 7. Monthly average total energy cost (2022)

TABLE II. SAVINGS ON ENERGY COSTS

Month	Baseline Cost (Naira/day)	Optimal Cost (Naira/day)	Baseline Energy (kWh)	Optimal Energy (kWh)	Energy Saving (kWh)	Cost Savings (%)
December	307.32	179.27	186.00	108.50	77.50	41.67
January	294.52	166.47	178.25	100.75	77.50	43.48
February	332.93	179.08	182.00	98.00	84.00	46.10
November	230.49	140.56	135.00	85.50	52.50	38.89

a depreciation factor, and operating and maintenance costs. The present worth of the money flow for the jth year is calculated as:

$$PV_j = \frac{Cf_j}{(1+r)^j} \tag{32}$$

where Cf_j is the money flow for jth year and r signifies the money rate.

Table III shows the present value of HSHP water heater. The economic metrics of this project are based on the assumption that optimal cost savings, operation, and maintenance costs will not change during the anticipated years. Furthermore, a discount factor of 4.25% was

TABLE III. DISCOUNTED PRESENT VALUE

Duration (years)	Initial	First	Second	Third	Fourth	Fifth
Initial investment cost Solar thermal collector cost (N) (124 260.00) Solar controller cost (N) (72 000.00) Cost of accessories (N) (15 000.00) Cost to install (N) (35 000.00) ZigBee switch controller (N) (13 5000.00)						
Total Investment cos (N)	(214 760.00)					
O& M costs (N)		(5500)	(5500)	(5500)	(5500)	(5500)
Expected annual benefit Optimal cost (N) (54 720.43) (54 720.43) (54 720.43) (54 720.43) (54 720.43)						
Money flow		49 220.43	49 220.43	49 220.43	49 220.43	49 220.43
Discount factor	1	0.96	0.92	0.88	0.84	0.81
Present value payback period	(214 760.00)	47 251.61	45 282.80	43 313.98	41 345.16	39 868.55

Year: present value, net present value
0: (214 760.00), (214 760.00)
1: 47 251.61, (167 508.39)
2: 45 282.80, (122 225.59)
3: 43 313.98, (78 911.61)
4: 41 345.16, (37 566.45)
5: 39 868.55, (2302.13)

applied, which reflects the time worth of money. Thus, the net present value is calculated by deducting the initial investment cost (IC) from the present value PV_j as follows:

$$\sum_{j=1}^{k} NPV = \sum_{j=1}^{k} PV_j - IC \tag{33}$$

Also, the discounted payback period (PBP) is computed by adding the year before the break-even to the result obtained by dividing the unrecovered cost of initial investment by the cash flow in recovery. This is further expressed as:

$$PBP = \beta_y + \left[\frac{-\sum_{j=1}^{k} NPV}{PV_j(\alpha_j + 1)} \right] \tag{34}$$

where α_j denotes the year before break-even and α_j. denotes last year with a negative NPV.

V. CONCLUSION

An optimal control strategy for a solar thermal system combined with a heat pump was presented in this paper. The control objective was to reduce the hybrid system's electricity costs while still fulfilling hot water demand. A generalized recursive discrete model, an optimization solver, and an algorithm based on mixed integer nonlinear programming were developed for this purpose. A novel optimal controller for the hybrid system was implemented in the MATLAB environment, and its performance was compared to the baseline ON/OFF controller. The proposed hybrid system optimal controller saves around 61.14% of electricity, resulting in a cost reduction of roughly 70.8% over the baseline model managed by an ON/OFF controller. Furthermore, the economic assessment shows that, compared to baseline HPWHs, the proposed hybrid system has a shorter discounted payback period and much greater revenue than baseline HPWHs. In comparison to the baseline heating system (HPWH), the HSHP system had the minimum LCC of N1, 030,523.48 and the lowest grid energy cost of N450, 734.00. The result from the NPV shows that the HSHP has a shorter payback period of 3 years and 11 months than the baseline model. The simulation results from MINLP optimization and MATLAB show that the optimal control strategy (OC) is more cost-effective compared to the baseline model. The optimal control strategy's energy cost is 62.60 N/kWh, while the baseline system's cost is 214.60 N/kWh. Also, the OC has the potential to save 61.14% more energy than the baseline system.

Availability of Data and Materials: The data that support the findings of this study are available on request from the corresponding author.

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