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Scheduling and economic analysis of hybrid solar water heating system based on timer and optimal control

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ABSTRACT

In this paper, an optimal control approach is modelled and applied to a hybrid solar electric water heater. The hot water consumption profile of a medium density household is considered. Real historic exogenous data obtained from a weather station in the region is used as input for the developed model.

The aim is to assess the cost saving potential the system can achieve under time-based pricing structure enforced by the electricity supplier in the region, while maintaining the desired temperature level of the hot water user.

As a baseline, the operation of a timer-based thermostatically controlled scheme, the most commonly used method of control to minimize the energy usage and in turn the costs, is simulated.

Comparisons between the operation of the HSWH with timer-based control and the optimally controlled HSWH presented a cost saving of 84.39% in the winter and 15.50% during summer period. Annual cost savings of 32.86% were noted. Additionally, the energy usage periods of the system are shifted to low demand regions of residential load profiles, decreasing the strain on the national electricity grid.

1. Introduction

Large amounts of energy are required to heat water, in households without space heating, the top consumer of electricity is the water heater. Approximately 40 to 60% of the total energy used in residential buildings can be allocated to water heating in South Africa [1]. Water needs to be heated from a lower temperature, usually close to the ambient air temperature, to the desired thermal level of the hot water user. An electric storage tank water heater (ESTWH), otherwise called a geyser in South Africa, has been the conventional device for suburban water heating within the country.

Nevertheless, the increase in the South African populace, economy and decrease in living standards has led to an energy generation deficiency which in turn resulted in an abruptly increasing electricity price. Eskom, the electricity supplier in South Africa, implemented an introduced energy management actions, such as energy efficiency (EE) activities, the use of renewable energy (RE) systems and incentives such as the Time-of-Use (TOU) electricity tariff [2].

As can be deduced from energy consumption statistics, one of the main culprits involved in high energy consumption is the traditional ESTWH [3]. In response to this issue, energy conservation educational material was presented by Eskom to assist in reducing the energy consumed by this water heater [4]. The educational material highlighted the importance of energy conservation practices and how to implement them. One practice which involves the lowering of the thermostat temperature of the ESTWH is one of the least expensive and easiest to implement. This method only required a once-off action whereby the setting on the thermostat is changed to a lower level in order to reduce standby energy losses [5]. A more costly and time-consuming approach at the entailed the insulation of hot water conduits leading to points of hot water consumption and the hot water storage tank in order to increase thermal resistance [6]. The third method requires personal discipline in the individual's daily hot water consumption routine. By making a habit of using less hot water during showers and bathing has a directly proportional relationship to the amount of energy consumed.

Additional educational material released by the electricity supplier through the broadcasting network of the country conveyed the importance of switching the ESTWH off during high energy usage periods to decrease the strain on the electricity grid. This results in a more equal distribution of the national energy usage profile and had no energy saving advantages to offer [7]. This however did present savings in cost when applied to residential areas where time-based pricing was enforced. The method of equalizing the energy consumption distribution

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of any given demand profile is the rough definition of demand-side management (DSM), DSM activities prevents the energy consumption to exceed the electricity generation of the country [8]. If the electricity supplier experienced a scenario where excessive energy was demanded as could be generated, the national power utility would be forced to shut down which would result in enormous economic implications and prove to be a threat to some of the lives of individuals residing in the country. A nation-wide shutdown or otherwise called a blackout can take several weeks to recover from [9].

Previous studies as in [10] on demand-side management (DSM) strategies on household water heating focused on peak load shifting techniques proved to be highly effective in most cases. These strategies make use of timer-based systems to relocate the time operation of higher energy devices to lower demand regions such as off-peak periods while successfully maintaining water temperature according to consumer requirements. Effectively designed DSM programs can limit the daily switch-on intervals to once or twice at minimized durations [11]. In the same way, autonomous optimal control of water heating systems based on DSM can result in higher savings in cost. This DSM method can provide the absolute maximum possible savings with a specific hot water consumption profile taken into consideration [12].

Alternative incentives implemented by the power utility include rebate programmes on installation costs of renewable source water heating systems, replacing the electrically supplied water heater so that no energy costs are incurred [13]. However, by replacing the electrical water heater introduces the disadvantage of reduced hot water availability. One way to eliminate this disadvantage is to use the renewable energy source water heater in conjunction with an electrically supplied water heater in order to compensate for the loss in hot water availability [14]. This system, referred to as a hybrid water heater has proven to be highly effective in practice in terms of reducing energy usage and cost when considering the system as a long-term investment. Furthermore, energy efficiency activities such as DSM and optimal control can be applied to these hybrid renewable systems which can result in higher savings in cost and energy when compared to a hybrid system that is not subjected to any such control approach [15].

The savings in energy and costs achieved while using the hybrid renewable energy systems in conjunction with energy efficiency activities have been the main attraction for the implementation of these systems and as a result gained popularity in recent years [16]. The most widely-used hybrid system across the world is the solar collector/electric water heater combination. This combined system ensures indefinite hot water availability. This solution appears to be exceptional on the surface, while closer investigation reveals that energy usage and costs can still be reduced making the system's operation suboptimal [17].

As a solution to this, a hybrid water heating system with an optimal control scheme is proposed to provide maximum savings in costs while maintaining the hot water user's desired water temperature. Two types of solar collector systems are mass produced in South Africa, these are the evacuated tube collector (ETC) and the flat plate collector (FPC). The (FPC) system coupled to an electric storage tank water heater (ESTWH) proved to be highly feasible for the region in the case study [18]. The feasibility of this system was determined based on hot water availability, low implementation and maintenance costs being the highest concern for consumers. The FPC is roughly 30% less costly to install compared to the evacuated tube collector (ETC) system. Furthermore, studies suggest that more than enough solar irradiance is captured to maintain a comfortable temperature level, even with a 10% less efficient heat absorbance factor compared to the ETC [19]. In addition, the ETC array has high replacement costs associated with evacuated tube replacements in the event of hail damage, whereas only the glass pane over the FPC need be replaced at low cost [20].

A popular control method implemented by hybrid ESTWH users to limit the frequency of switching-on periods is by making use of a timer system. The timer-based control method allows the user to switch the ESTWH ON at a specific time before hot water is required, when hot water is not required, the timer will be set to maintain an OFF state. Another method of minimizing power usage of electric water heaters is to lower the thermostat temperature so that the resistive element is supplied with energy for shorter durations [21].

An optimal control approach can maintain desired temperatures at times when hot water is required and minimize costs by supplying energy to the auxiliary water heater in the cheaper regions of a TOU tariff structure. This method of control based on the TOU tariff structure was implemented on the HSWH system and resulted in significant cost savings for the consumer as discussed in [22]. The recent study in [22] provided insight on the economic feasibility of an optimally controlled hybrid solar water heater compared to a traditional thermostatically controlled ESTWH system without a renewable energy water heating source in the central region of South-Africa. The aim of this paper therefore is to evaluate the effectiveness of a similar optimal control approach applied to a case study based in a different location (Durban in KwaZulu Natal province) where lower levels of solar irradiance is experienced. The optimal system is compared to a traditional water heater with timer-based control coupled to a solar collector in terms of energy costs incurred in an economic analysis in order to justify the use of an optimally controlled system. The use of the timer-based system is widely used by consumers due to the ease of installation, operation and cost effectiveness it offers. Furthermore, an economic analysis and comparison between this control method and the optimal approach can broaden the understanding of the energy consuming populous of the potential cost savings that can be achieved. In retrospect, the purpose of this study is to evaluate the economic feasibility of an optimal controlled hybrid water heating system compared to the closest competitor in terms of energy management.

This paper is organized as follows: Section 2 describes the mathematical formulation of the optimal control model of a hybrid indirect flat plate solar/electric water heater; Section 3 presents exogenous data for the case study used in this study. For effective evaluation of potential cost savings of the proposed optimal control scheme, a baseline model which consists of a timer-based controlled ESTWH coupled to a FPC is presented in Section 4. Results from the simulated optimally controlled hybrid solar water heater (HSWH) are discussed in Section 5. The economic analysis of the system is given in Section 6. Conclusions and recommendations are presented in Section 7.

2. Mathematical model formulation

2.1. Dynamic model of the hybrid solar/electric water heating system

In Fig. 1, the hybrid water heating system is shown, which includes an indirect flat plat collector (FPC) with the heat exchanger inside the collector. The FPC is coupled to an ESTWH with a single electric resistive element. A circulation pump forms part of the collector loop to force water through the system. The pump operates automatically through a temperature differential control circuit and can be seen as an independent system. The control circuit consists of temperature probes which activates the pump when a specific difference is detected between the hot-water outlet and cold-water inlet valves of the collector. This system guarantees that when solar irradiance is insufficient or nonexistent, the pump will remain off so that cold water is not repeatedly being circulated through the storage tank [23]. This is essential to prevent a temperature loss of the water supplied to the consumer.

All energy gains and losses in the hybrid arrangement are identified in order to form an energy balance equation. The energy gained from the solar collector is noted as the primary energy source of the system [24] shown in Fig. 1 and denoted in Eq. (1).

$$Q_{coll} = A_c\,[F_R(\tau\alpha)G(t) - F_R U_L(T_{co}(t) - T_m(t))] \tag{1}$$

Where: A_c is the collector area (m^2), F_R F_R is the collector heat removal factor, $\tau\alpha$ is the transmittance absorbance factor, $G(t)$ is the variable