Energy Optimization and Management of Electric Water Heaters using Direct Load Control

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ABSTRACT

For years, utilities have used traditional demand response (DR) programmes to send out signals to consumers to reduce electricity consumption at times of high stress on the grid. Now, a new generation of communication and control technologies can enable "demand flexibility" by enabling pre-selected loads to periodically respond to changes in electricity supply levels and other market signals. Electric Water Heaters (EWHs) are regarded as effective energy storage devices. Thus, they are considered ideal candidates for DR. This paper presents the results of the pilot project that was conducted at the CSIR campus. The aim of this pilot study is to demonstrate the use of direct load control of EWHs for strategic load conservation and load shifting. The results showed that both energy and money can be saved by scheduling the EWH operations and also shifting the load to off peak periods. The results showed energy consumption reduction of about 36% and cost reduction of about 41%.

1. INTRODUCTION

Climate change and energy security are the pressing issues globally today. In South Africa, Green House Gas (GHG) emissions is about 1.1% of the global emissions and buildings are one of the largest consumers of electricity and account for over 25% of GHG emissions [1]. Thus, the building sector provides opportunities for reducing CO2 emissions through energy efficiency and behavioural change. Moreover, the residential sector uses about 20% of the total electricity generated in South Africa. From 7am to 10am in the morning and 5pm to 9pm in the evening, residential demand is up to 35% of the total demand required [2]. Energy for water heating is one of the largest sources of households energy use and it accounts for 35% of the total households' energy consumption. There are nearly 5.4 million Electric Water Heaters (EWHs) in South Africa contributing about 2,940MW of electricity to the evening peak [3].

For years, utilities have used traditional DR programmes to send out signals to consumers to reduce electricity consumption at times of high stress on the grid. Now, a new generation of communication and control technologies can enable "demand flexibility" by enabling pre-selected loads to periodically respond to changes in electricity supply levels and other market signals. EWHs are regarded as effective energy storage devices. Thus, they are considered ideal candidates for DR. For this reason, it is valuable to have control over water heaters to use them when the demand for power is low and turn them off during periods of peak demand. Ripple relays to control geysers have been used in South Africa for more than half a century. The main purpose of the ripple relay is to shift the heating load of EWH out of peak demand times by switching off a large number EWHs for short periods during peak demand, however ripple relay technology is a unidirectional controller with no consideration for the comfort of the user/customer [4].

The aim of this pilot study is to demonstrate the use of direct load control of EWHs for strategic load conservation and load shifting at the CSIR Pretoria campus. Six (6) smart water heater controllers were installed at different buildings at the CSIR Pretoria campus and the energy consumption data recorded by these controllers is analysed in this paper. The electricity pricing method was also considered to obtain the financial benefit of employing these control strategies.

Section 2 of this paper outlines the modelling of the EWH. Section 3 presents the pilot setup. The results of the pilot study are analysed in section 4 and finally the conclusions are drawn in Section 5.

2. ELECTRIC WATER HEATER MODEL

2.1 Energy model

The temperature inside the tank depends on both the temperature of the air surrounding the tank and the amount of warm water that is extracted for usage events. The amount of energy required to heat the water in the EWH tank can be calculated using the following equation [5]:

$$E_{heat} = m_{tank} Cp \Delta T \ \ [kWh]$$

Where: E_{heat} is the energy required to heat the entire container of the EWH tank; m_{tank} is the mass of water contained in the EHW (kg); Cp is the specific heat capacity of water (kJ/kg. °C); and ΔT is the temperature difference between the cold and warm water (°C).

2.2. Thermal Model

The objective of the EWH thermal modelling is to determine the link between parameters of EWH and the total power consumption. These parameters consist of physical characteristics such as water temperature, ambient temperature and water usage. A single element domestic

EWH is considered here. A comprehensive one-node and two-node differential equation model for the heat transfer process in an EWH is presented in references [2], [3] and [4]. This model is based on the energy flow analysis and yield a method to determine the temperature of the water in the tank as a function of time. The first order differential equation model of the thermal characteristics of temperature inside the tank is

$$Th(t) = Th(\tau)e^{-(1/R'C)(t-\tau)} + \{GR'T_{out} + BR'T_{in} + QR'\}\left(1 - e^{-(1/R'C)(t-\tau)}\right) \ [°C]$$

Where:

τ is the initial time (hour); T_{in} is the incoming cold water temperature (°C); T_{out} is the ambient temperature (°C); $Th(t)$ is the water temperature inside the EWH at time t (°C); Q Power consumption of the heater (W); R is the thermal resistance (m^2.°C/W); SA: tank surface area (m^2); $G = \frac{SA}{R}$ (W/°C); F is the hot water flow rate (gallons/h); $B = F \times 3.785 \times Cp$ (W/°C); One liquid gallon of fresh water weighs roughly 3.785 kilograms (kg) at room temperature; Cp is the specific heat of water (Ws/kg.°C); C is the equivalent thermal mass and is given by $C =$ vol.$\times \rho \times Cp$ (Ws/°C); ρ is the density of the water; vol. is the volume of the tank (m^3); $R' = 1/(G + B)$ (°C/W).

2.3 Temperature decay model

The temperature decay of the water inside the EWH in the absence of usage events can be modelled using the following equation as presented in reference [1] [5]:

$$T_{inside}(t) = T_{amb} - [T_{amb} - T_{inside}(0)]e^{\frac{-t}{CpRm_{tank}}} \ [°C]$$

Where: $T_{inside}(t)$ and $T_{inside}(0)$ are the temperature, in $°C$, of the water inside the tank at time t and at time 0 respectively; R is the limped thermal resistance of the EWH (m^2. °C/W); $T_{amb}$is the ambient temperature ($°C$). For his analysis, we assume a low set point of $50°C$ and a low ambient temperature of $10°C$ in order to calculate the temperature decay for the worse-case. The standing losses of the EWH in South Africa must meet the minimum specification as outlined in the South African National Standards (SANS) 151 (Reference), which stipulates that the maximum tolerable standing losses for a 200L EWH at $65°C$ is 3.02 kWh. As a result, the thermal resistance of the EWH is $17.52\frac{°C.day}{kWh}$.

2.4. HOT WATER USAGE MODEL

The consumers' hot water usage depends on the time of day and varies from household to household. Meyer et al. [12] measured the hot water consumption for townhouses in Johannesburg over a period of 1 year. Thirty townhouses (10 in each category of low-, medium- and high-density) were fitted with digital flow meters of the water heater, and measurements were taken with a 60-minute-interval recorder. All the water heaters thermostats were set at 65°C, and measurements were taken over a period of 1 year. The results of the study are illustrated in Figures 1 and 2 below. In our analysis we used Low-density townhouse hot water consumption data. It can be seen from Figure 1 and 2 that a morning peak and an evening peak, of approximately the same size, occur twice a day. The morning peak for a low-density townhouse occurs at 08:00 and the evening peak occurs at 21:00.

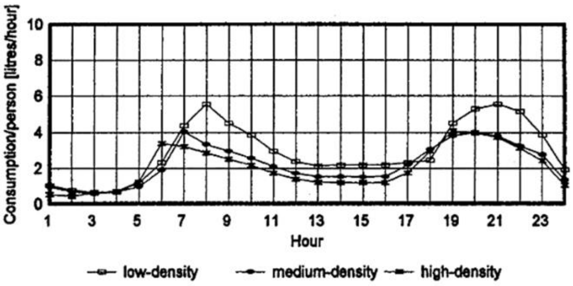

Figure 1 Hourly hot water consumptions per person/day at a temperature of 65°C during weekdays in summer [11].

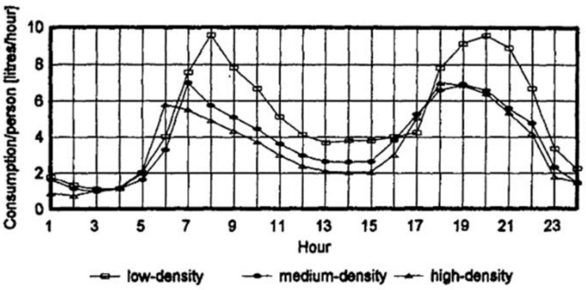

Figure 2 Hourly hot water consumptions per person/day at a temperature of 65°C during weekdays in winter [11].

3. ELECTRIC WATER HEATER CONTROLLER PILOT SETUP

This section describes the setup of the pilot study. Based on the data obtained from the recent CSIR Energy Audit conducted for the Energy Autonomous Campus, water heaters that are more than 100 litres in capacity have been identified as potential to carry out the pilot because they draw more power as compared to smaller EWHs. The Geasy smart water heater controllers were installed at six (6) 200 litre water heaters. The smart controller measures and controls the water flow, the temperature of hot water, power drawn by the EWH and ambient temperature. The bidirectional communication is performed using a mobile cellular network. Monitoring of data and control of the device is done through the online platform provided by the supplier of the controllers.

3.1 Electric wiring

Figure 3 illustrates how the smart controller was installed. The sensors are installed as show in Figure 4. The device installed on campus uses only one sensor, the outlet temperature sensor. The reason being that the scope of this project is only limited to the power used by the EWH not the water usage.

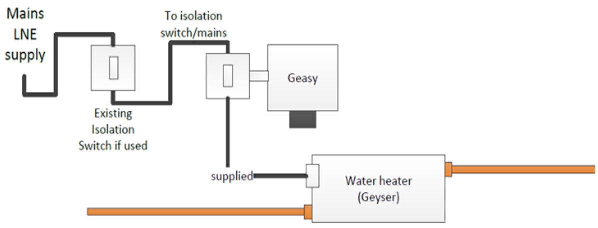

Figure 3 Circuit Wiring Diagram

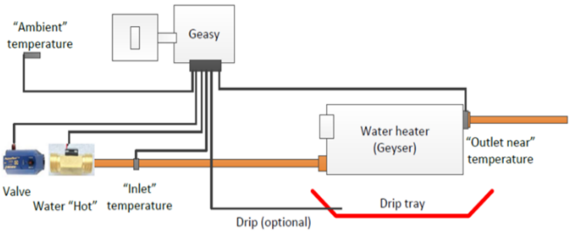

Figure 4 Sensors Installations

3.2 Building Characteristics

We have simulated the power consumption of six (6) 200 litres EWHs. The type of buildings in which these EWHs are installed are guesthouses accommodating CSIR employees and at the CSIR international conversion centre (ICC) bathrooms. The data recorded at the guesthouses were used to understand the domestic use of hot water, while the data captured at the ICC bathrooms were used to understand hot water usage in buildings in the commercial sector.

4. RESULTS

4.1 Baseload Energy Consumption

The data was recorded for two months without employing any schedule or control on the EWH. The chosen dataset was captured for over 2000 hrs. This was done in order to measure the baseload energy consumption. Figure 5 shows the average energy consumption of the 200L EWH. As expected the consumption in winter is higher than in summer.

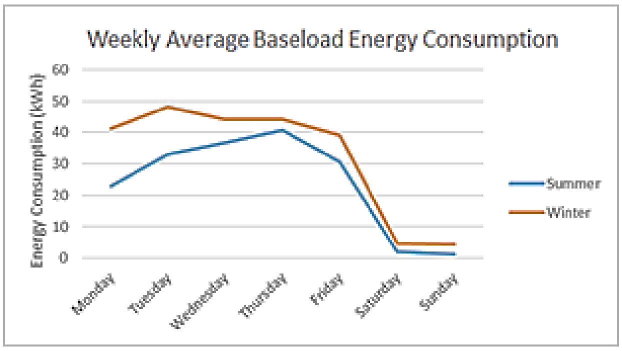

Figure 5 Weekly Average Baseload Consumption

4.2 Case Study 1: Strategic Load Conservation

The purpose of this case study is to analyse the effects of load conservation control strategy on EWH load. This was done by switching off EWHs during periods of none occupancy and switching them on again during working hours. Normally, the EWHs will be left on even during the weekends and after office hours when people are not there. The following schedule was employed, as shown in Table 1:

Table 1 Heating Schedule

	Mon	Tue	Wed	Thu	Fri	Sat	Sun
Start	5 am	5 am	5 am	5 am	5 am	Off	Off
End	4 pm	4 pm	4 pm	4 pm	4 pm	Off	Off

4.3 Consumption after scheduling

The graphical representation of the energy consumption before and after scheduling is illustrated in Figure 6 and 7, respectively. When the temperature drops below the lower limit, the EWH switches on and heats the water until it reaches the upper limit. However, when an EWH is switched off for a prolonged period of time (i.e. several hours) the temperature of the water in the tank continues to decrease below the lower limit, this is observed on Mondays. When the EWH is switched on again, it must reheat the water that has cooled below the set temperature, which is referred to as the cold load pickup [6]. The scheduling saved about 36% of energy consumption per week.

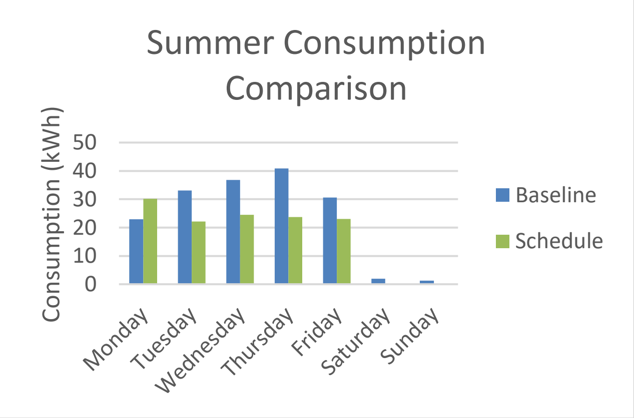

Figure 6 Summer Consumption Comparison

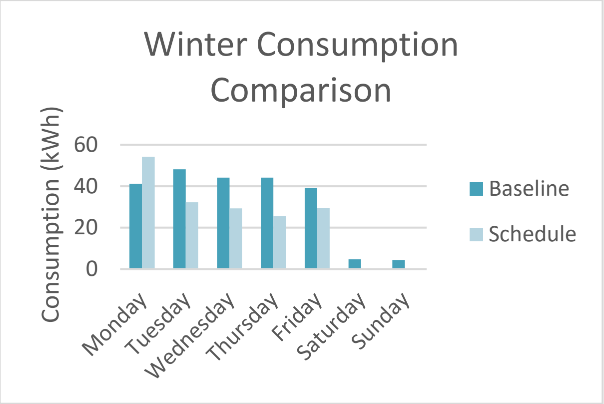

Figure 7 Winter Consumption Comparison

4.4 Case Study 2: Load Shifting

The purpose of this case study is to analyse the effect of load conservation and load shifting control strategies. Figure 8 shows an actual average load profile of a 200L EWH after employing load conservation strategy and how it coincides with the peak demand period. Also, the cold load pick up falls under peak demand period and this could have a significant impact on the cost of heating water in the morning. To avoid this, the load was shifted by 3 hours in the morning as illustrated in Figure 9. According to the thermal model of EWH, presented in section II, it takes 5-6 hours before the water temperature could reach the minimum temperature. Shifting the load by 3 hours in the morning would not impact the comfort of the users. The City of Tshwane TOU tariffs were used to determine the cost savings made by the implementation of both the load shifting and load conservation strategies. The cost reduction for implementing both load conservation and load shifting is about 41%.

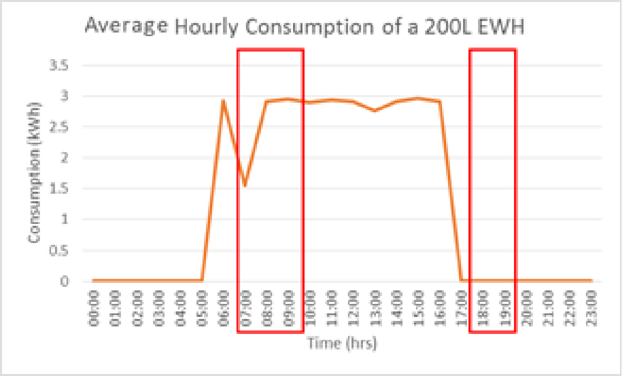

Figure 8 Strategic load conservation energy consumption load profile

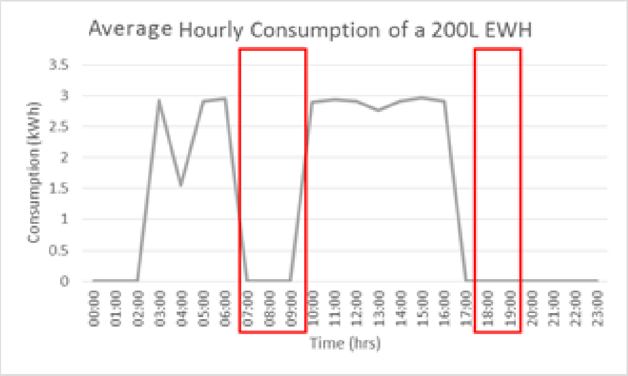

Figure 9 Energy consumption load profile after load shifting

5. CONCLUSION

This paper demonstrates the impact of strategic load conservation and the use of load shifting control strategies on EWHs. The electricity pricing method was also considered to obtain the financial benefit of employing these control strategies. The real energy consumption data of an EWH was used to analyse the impact of these direct load control strategies. Both operational and physical characteristics of the EWH were considered to formulate a demand response strategy. After the analysis it was found that both load conservation and load shifting control strategies reduces energy consumption which is financially profitable. By using proposed methods, it can be concluded that the EWHs are able to participate in the demand response event. It was also observed that the cold load pick up can have an adverse impact and must be managed in order to optimize the cost savings.

7. REFERENCES

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