AN INTELLIGENT WATER HEATER WITH WI-FI ACCESS TO SUPPORT DEMAND-SIDE MANAGEMENT

J.W.K. Brown and M.J Booysen*

* *Department Electrical and Electronic Engineering, Private Bag X1, Matieland 7602, South Africa.*
Email: mjbooysen@sun.ac.za

Abstract: In the current climate of energy shortages and attempts to reduce electricity consumption, demand-side management has proven to be effective and popular. One implementation of demand-side management has been to provide the end-user with control over the ubiquitous houshold water heater (called geysers in South Africa). This paper presents a novel way to interact with water heaters, in which water heater control and monitoring is provided on a website that is accessible through a Wi-Fi hotspot interface. Both of these are hosted by the processor that controls electricity supply, tank temperature, and water supply; and monitors electricity consumption, water consumption, inlet, outlet and tank temperatures. The proposed system also provides protection against inevitable mechanical failure of the water heater, by detecting leaks and bursts, and by stopping water and electricity supply in such scenarios. This paper shows that the proof of concept is realisable in terms of cost, functionality, and energy savings.

Key words: Demand-side management, intelligent control, user interface, water heater, geyser, power saving.

1. INTRODUCTION

The demand for electricity in South Africa is rising and rapidly approaching generation capacity. Incidences where demand had the potential to exceed generation capacity have been evidenced in recent years by the institution of rolling blackouts, in an effort to maintain grid stability [1]. Currently, at peak load, South Africa is operating at a surplus capacity of just 8% - just over half of the typical international minimum of 15% [2]. When power generation plants are taken offline for necessary maintenance or repair, this can drop even further.

This situation has resulted in Eskom having to take measures to increase the generating capacity, in order to maintain stability of the power system. These measures included the reopening of power plants that were mothballed in the 1990s, the construction of open cycle gas turbine plants, and the construction of two new power stations. Medupi and Kusile stations add a capacity of 9564MW to the national grid, an additional 21.6% [3] [4]. However, all of these methods take time to implement. Returning a mothballed power station to a completely operational state takes approximately three to four years. While the construction of a new coal power station typically takes eight years [3] [4].

Eskom has instituted the shorter term solution of Demand Side Management (DSM) in the interim. DSM can be summarised as reducing the demand for power through a change in consumer behaviour. This is achieved by causing the consumers to use less power by providing them with the incentive and means to do so. The incentive is provided through the implementation of power tariff increases of 78% between 2008 and 2011, to fund the the production of the aforementioned additional generation capacity. Additionally, power tariffs are set to further increase by 8% per annum [1]. So far, implementations have included the installation of Compact Fluorescent Lights (CFLs) and solar water heaters in many homes and workplaces, as well as pilot schemes to reduce power use during times of peak load.

Applications that aid in the implementation of DSM have the greatest potential to alleviate the situation of excess demand in the short term. Water heating is the area of greatest electricity consumption in the residential sector. It offers the greatest opportunity for overall power usage savings and peak power use reduction [5]. Applications that focus on this area will offer the greatest per-unit return.

One of the suggested implementations to DSM has been to retrofit control systems to the to existing water heater installations [6]. Water heating contributes 35% of residential electricity consumption [5], and is mostly uncontrolled. The solution proposed in [6] provides both control and metering information to the user. This monitoring and control enables the user to implement usage strategies that make more efficient use of electricity. Another advantage of targeting this source of power use is that water heaters have the ability to store energy in the form of heat. This can be leveraged to shift power use away from times of peak load to times of typically low consumption, 2AM for instance, which reduces the peak load on the the power system.

1.1 Contribution

This paper presents a novel way to interact with the ubiquitous household water heater control system, such as the one in [6], and also proposes novel control strategies that leverages the novel interface. The system allows the user to interact with the water heater through an interactive and user-friendly web site, hosted by a Wi-Fi access point (hot-spot) that is hosted by the control system. The user connects to the Wi-Fi hot spot with any Wi-Fi enabled device (e.g. smartphone, tablet, laptop) in-range of the water heater, and uses any browser to access the features of the water heater that are presented as an interactive web site. The web site gives the user control over the element state (on/off), set temperature, control scheme, and water supply (on/off). The user is also able to monitor various indicators, including element state (on/off and power), water flow rate (litres/minute), tank temperature, inlet temperature, outlet temperature, daily power consumption, daily water consumption.

Through providing this interface, the user is empowered to apply their own supply-side management in an easy way with immediate feedback. The results from the tests of the unit and the unit itself demonstrate both the feasibility and the benefits of intelligent control.

The rest of this paper is structured as follows: Section 2 summarises the research that was done to contextualise the work done in this paper. Section 3 records the design process that was followed to create the unit. Section 4 provides the system's tests results as applied to the water heater used. Finally, in section 5, a conclusion is reached as to whether the unit met the objectives and possible further work that could be done is suggested.

2. RELATED WORK

The authors of [6] analysed the data from water heater control units installed in several homes to determine the potential energy savings of installing a control unit. The energy savings from operating a water heater on a timer was proven theoretically and validated empirically. It was found that, not only does a the installation of a control unit result in reduced energy usage, it also changes the behaviour of the user. This behavioural change results in a further reduction in energy usage and is driven by the feedback that a control module can provide [6]. The control unit used for this study did not include a method of measuring the water consumption and did not include ease of installation and user interaction as a focus. Bot of these could adversely affect the wide scale acceptance of the unit.

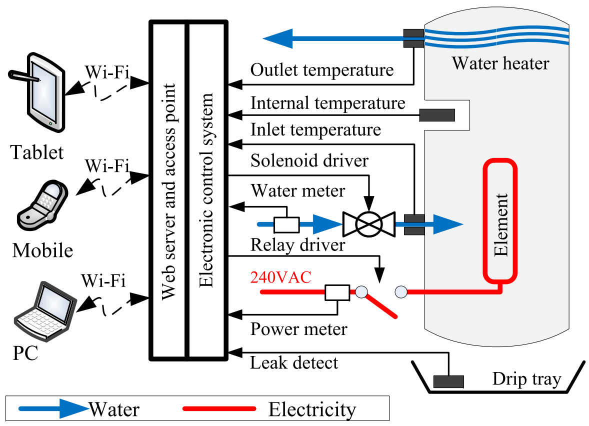
In [7], Müller et al. presents the implementation of a water consumption measurement and control solution, to enable remote utility monitoring and control. This was done through the inclusion of a solenoid valve in the water supply and the design of an orifice flow meter. It was determined that the meter operated to within 3% accuracy and provided an accurate indication of water consumption rates [7]. However, the orifice flow meter uses a pressure differential to measure water flow *rate*, which makes it unsuitable for volumetric metering (any meter inaccuracies will integrate and decrease accuracy over time). Moreover, the unit was not specifically designed for water heater control, but rather as a proof of concept for the control and monitoring of general utilities.

Nel et al. [8] implemented a smar phone application that enables users to monitor the status of a water heater with the aim of informing the user of their historical and near real-time water consumption. The application takes the form of an application for Android-enabled devices. The application is highly intuitive and the custom GUI presents the information is a manner that is easy to assimilate [8]. A drawback of this system is that it relies on pre-installed hardware and the assimilation of separate monitoring systems which increases the complexity and cost. Moreover, the system relies on cellular networking and cloud-hosted services.

3. SYSTEM DESIGN

This section describes the system presented in this paper. The system diagram shown in figure 1 shows the relationship between the various parts of the system, hereafter referred to as the intelligent water heater module.

Figure 1: System diagram



3.1 *Processing*

The Beagle-bone Black was chosen to provide the necessary processing capacity for the intelligent water heater module. The Beagle-bone Black is a single board computer that is approximately the same size as a credit card. It typically runs a version of the Linux kernel. The Debian operating system was used. Hardware Input/Output functionality is provided by two pin headers, which include dedicated serial and analogue input pins.

3.2 *Sensors*

Temperature sensors that provide analogue output (10 mV for degree Celsius) were chosen as the temperature sensor to measure the temperature of the water heater at the inlet, outlet and internally. The sensors were secured to copper pipe at the inlet and the outlet to the water heater and to the rear face of the element flange. In the case of this system the legs of the sensors were electrically insulated before the sensors were secured. This output monitored by the Beagle-bone.

The water meter chosen to measure the water usage is the Elster Kent V100T PSM volumetric water meter [9]. This meter has an optional reed switch that outputs a pulse every half litre. These pulses were input counted by the Beagle-bone and were used to determine the water flow and usage.

The power was measured by means of a specialised system-on-chip measurement IC which communicates with the Beagle-bone via a serial connection. The power measurement IC (PMIC) used for the measurement was the CS 5490 by Cirrus Logic. This PMIC measures voltage, current and power factor [10]. Complete isolation from the 220V AC supply was desired for the PMIC, so the voltage and current were measured through voltage and current transformers respectively. This unit draws its power from a 3.3V voltage rail on the Beagle-bone and communicates with the Beagle-bone via a serial connection.

A switch was included that is used to detect structural failures of the water heater. In its current form, it is manually activated but can be easily adapted to close if a burst or leakage is detected in the drip tray. The switch is connected to the Beagle-bone. Closing the switch activates the water cut off valve, cuts off power to the element and alerts the user by means of the user interface.

3.3 *Actuators*

The element was controlled using a solid state relay from ECE [11]. A drawback of using solid state relays is that they can overheat if not properly cooled. To provide sufficient cooling the relay was bolted to an aluminium heat-sink. As an additional protection measure the relay was fitted with a thermal fuse. The fuse is placed in series with the control signal to the relay and fastened to the heat sink to be at the same temperature as the relay. The necessary 4V and current to switch this relay and the mechanical relay used to switch the solenoid valve, was provided by means of a Darlington pair switched by one of the general Input/Output pins on the processing unit.

Water flow control was implemented using a valve activated by a solenoid. The valve requires a 24V AC voltage in order to be switched on. This voltage was provided by the voltage transformer that was used as part of the power supply for the system.

3.4 *Power supply*

The Beagle-bone and the much of the circuitry associated with the sensing and actuation require a power supply of 5V to operate. The power measurement IC (PMIC) requires 3.3V and a scaled AC voltage to measure. Finally, the solenoid valve requires 24V AC to operate. The power supply was designed to supply all the these required voltages in such a way that additional supplies will not be needed and the intelligent water heater module can draw its power from the supply for the water heater itself.

3.5 *Software*

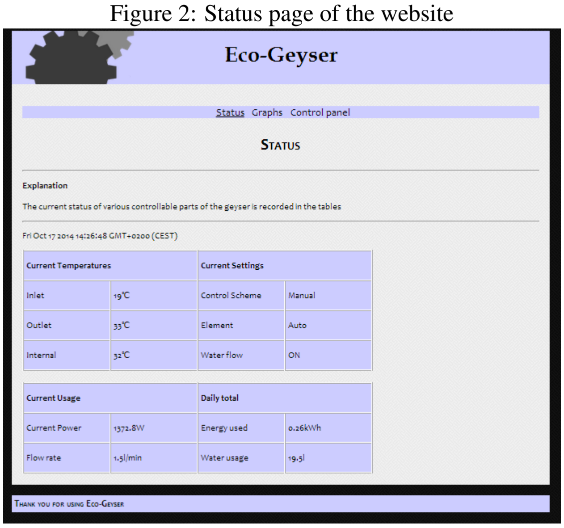
The programming language chosen to implement the control system was JavaScript. This was done for several reasons. The first of these was the presence of several libraries and modules that would be invaluable in the development of a web server that would also have the ability to manipulate the hardware on the Beagle-bone Black.

3.6 *User interface*

The user interface for the unit was provided by means of an interactive website hosted on the Beagle-bone and accessed through a Wi-Fi access point created by the module. The wireless access point was implemented by using the TPlink Wireless N Nano Router. The router was connected to the Beagle-bone via an Ethernet cable and supplied with power via a USB cable connected to the USB port on the Beagle-bone.

The website for the UI was implemented in three pages. The pages were Status, Graphs and Control panel. These pages were written in html 5. JavaScript was used to provide dynamic content and communication with the server.

Figure 2: Status page of the website



The status page was designed to give the user an indication of the most important parameters of the intelligent water heater system at a glance.These parameters are current values being measured and the active control scheme. The three temperature measurements, current water and power usage and daily totals for water and energy usage are given. This page can be seen in figure 2.

The Graphs page displays the current temperature values, water usage and power usage. For each data point the graph indicates the value and the time at which the value was recorded. This will save the user from having to determine the time that the datum was recorded using the update interval. This page is shown in figure 3.

Figure 3: Control panel page of the website

The control page presents the user with the option to select one of the three different control schemes; Manual, Temperature and Eco. The user is also given the option to override control of the water heater element - turning it either on or off. The water cut off control is also available on this page. This page is shown in figure 4.

3.7 Control schemes

The three control schemes available to the user are Manual, Temperature, and Eco.

Manual control places all control of the heating element of the water heater with the thermostat. Water heater operation in this mode is identical to that of a water heater without a control module. The only benefit of the intelligent water heater module in this mode is the feedback that it provides.

Figure 4: Control panel page of the website

In the Temperature control scheme, the control module cuts power to the element when it reaches a desired temperature. The user can set the desired temperature on the interface.

The Eco scheme operates in the same way as the Temperature Control scheme with the addition that users are able to specify a times at which they desire hot water. The system will then determine when the water heating needs to begin to provide hot water at the desired time and only switch on at that point.

3.8 Demonstration unit

Once completed the system was installed on a ten litre water heater as a test and demonstration set up which can be seen in figure 5.

4. RESULTS

The test and demonstration set up was used to test the performance of the unit. Various aspects of the unit were tested: the accuracy of the sensors, the potential energy savings for the given test water heater, power usage of the system, and finally we give an estimate of the cost of the system.

4.1 Sensor tests

The power measurement and temperature sensors were tested against a the measurements obtained using a commercially available power measurement unit and thermometer respectively. From this test it was determined that the Power measurement was accurate to within 3% accuracy and the temperature measurement was accurate to within 9%. As a comparison the built in thermostat of the water heater was only accurrate to within 5%. The reason for the inaccuracies of the temperature sensors is that they hare decoupled from the water. These inaccuracies can, however, be overcome by modelling

Figure 5: Control module installed on demonstration and test setup

the heat transfer between the water and the sensor, to accommodate the differences.

According to the SABS, the water measurement unit is accurate to within 2% at the flow rates experienced.

4.2 *Power saving tests*

The potential of the unit to save power was tested by comparing the consumption of the unit under the Manual control scheme with the consumption when controlled by the Temperature and Eco control schemes. The Temperature control scheme was tested at a 15°C reduction in temperature from nominal. This resulted in a 30% power saving. Similarly, a timed test of the Eco control setting at nominal temperature resulted in a 30% saving in power when compared to the consumption of the unit under Manual control.

The results of these tests are highly dependent on several different factors; size of the water heater, use cycle, hot water consumed during the use cycle, etc. However the results are more than sufficient to prove that an intelligent water heater unit such as this has the potential to affect significant power savings.

4.3 *Power use*

The power consumption of the control module is approximately 9 W when the unit is under power, hosting the access point, measuring the power and water flow, and monitoring the three different temperatures, which is roughly 5% of the daily consumption of a household water heater. The system can be significantly optimised, by reducing the processing power of the Beagle-bone black, and by using switch-mode regulators. The power consumption increases to approximately 24 W when the solenoid valve controlling the water flow is activated. It is therefore recommended that a normally open water flow control is implemented in future, to further save energy.

4.4 *Unit cost*

The prototype module was assembled for a price of approximately 2250 ZAR. If components were to be sourced in bulk and more cost effective suppliers were located, this figure could drop to an estimated price of 1550 ZAR.

This initial outlay, even with the added installation cost, can be recovered in the first year in the form of reduced electrical bills.

5. CONCLUSION

Further work that could be done on the intelligent water heater module could include the following. Wi-Fi access to the unit could be provided using a USB dongle instead of using a router. This will make the unit more cost effective and reduce the footprint of the unit. Moreover, this would allow for the implementation of a DNS server on the Beagle-bone which will present the user with a more user friendly URL when accessing the website (at the moment, an IP address has to be entered). Additionally, data logging could be implemented in order to provide the user with monthly or even yearly totals for power usage.

Conversely the unit could be simplified - if the user interface is modified control could be provided by a micro-controller. This would provide a smaller, cheaper unit at the expense of the user interface but theoretically none of the functionality. The user interface would be provided by means of a GSM modem which uploads the data to a central server. This would enable the user to control the unit as long as they have internet access. This adaptation is currently under development.

REFERENCES

[1] N. Fisher, "Balancing South Africas Energy Poverty and Climate Change Commitments," 2014.

[2] Eskom. Load management: Surplus capacity. [Date Accessed: 2014/10/06]. [Online]. Available: http://www.eskom.co.za/Whatweredoing/ElectricityGeneration/LoadManagement/Pages/Surplus_Capacity.aspx

[3] B. Majola, "Newly re-opened Grootvlei Power Station contributes to keeping the lights on," 2013.

[4] Eskom, "Cop 17 fact sheet: Kusile and medupi," 2011.

[5] S. de la Rue du Can, V. Letschert, G. Leventis, T. Covary, and Xia, "Energy efficiency country study: Republic of South Africa," 2013.

[6] M.J. Booysen, J.A.A. Engelbrecht, and A. Molinaro, "Proof of concept: Large-scale monitor and control of household water heating in near real-time," in *International Conference of Applied Energy: (ICAE 2013)*, Jun 2013.

[7] R. Müller and M. Booysen, "Household electricity and water monitor and control with cellular communications and web interface," in *South African Universities Power Engineering Conference (SAUPEC)*, Jan 2014.

[8] P.J.C. Nel, M.J. Booysen, A.B. van der Merwe , "ICT-enabled solutions for smart management of water supply in Africa," in *International Conference on the Use of Mobile Information and Communications Technology in Africa (UMICTA 2014)*, Dec 2014.

[9] Elster Kent Metering, *ELSTER KENT V100T PSM Volumetric Water Meter*, 2009.

[10] Cirrus Logic, *Two Channel energy measurement IC*, 2013.

[11] ESR, *Solid state relay*, 2002.