

Saving on household electric water heating: What works best and by how much?

P.J.C. Nel*, M.J. Booysen*, B. van der Merwe†

*Department of Electrical and Electronic Engineering, Stellenbosch University, Stellenbosch, South Africa.

†Department of Computer Science, Stellenbosch University, Stellenbosch, South Africa.

Email: mjbooyesen@sun.ac.za

Abstract—Electric heating of water for domestic use is a substantial component of total household energy costs. Thermal energy in a water heater is either used (as warm water) or lost to the environment. Various approaches to reduce the losses and improve the efficiency of these notoriously inefficient and costly water heaters have been proposed and are employed. However, given the complex factors at play, making sense of the savings approaches and choosing the right one for the right use case is not a simple task and often misunderstood. This paper addresses this problem by comparing some of the commonly employed approaches, including schedule control, change in set temperature, use of thermal insulation, and reduction in consumed volume. We also compare the impact of environmental factors, such as changing the ambient temperature around the water heater and the cold inlet temperature. The results show that for the consumption profiles and use cases evaluated, schedule control is the most effective, followed by insulation of the tank and piping. Combined, these two interventions save up to 25%. We also find that the effect of the temperature of the cold inlet water dwarfs that of the ambient temperature, is in line with other approaches, and means the installation status quo needs to be reconsidered.

Index Terms—Understanding; perception; electric water heaters

I. INTRODUCTION

Household water heating, which accounts for as much as 32% of household electricity consumption where Electric Water Heaters (EWHs) are used, is notoriously inefficient and costly in terms of energy consumed.

EWHs consume energy through two main factors: Standing losses and consumption. Standing losses (thermal energy losses to the environment) is as a result of the temperature difference between the water in the EWH tank and the temperature of its surroundings, and is a function of thermal insulation of the EWH and surrounding pipes to the environment. The energy lost due to use is equal to the net effect of the warm water leaving the EWH and the cold water entering the EWH. The thermal energy in the water (enthalpy) is a function of the volume of warm water used and temperature of the water used.

Therefore, the energy consumed to heat water can be managed through several approaches that address these factors. The approaches include curtailment actions, such as shortening shower times (i.e. **reducing the volume** of water consumed) or lowering the **set temperature** of the appliance. Furthermore,

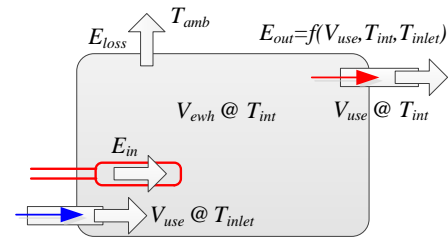


Fig. 1. One-node state energy flow.

users can implement efficiency actions that include the installation of a **thermal blanket or pipe insulation**. A user can also use **timer control** to intermittently switch the EWH on and off, which has been shown to reduce the standing losses by as much as 16% [1].

Other factors that influence the energy consumption of the EWH that the user has less control over after installation are: **tank size**, as a larger tank surface area causes larger environmental losses if the water in the tank is underutilised; the **ambient temperature** around the EWH, which impacts the standing losses since the temperature difference is greater; and **cold water inlet temperature**, which impacts the usage losses in two ways: the water consumed is replaced by colder water that needs to be reheated, but also that more or hotter warm water is required to create the desired temperature at warm water outlets if the mixed cold water's temperature is lower.

The one-node lumped model of an EWH is shown in Figure 1

A. Standing losses and ambient temperature

The ambient temperature has a direct influence on the standing losses of an EWH. This is because the amount of heat dissipated by the EWH tank is proportional to the temperature difference between the air outside the EWH tank and the water inside the EWH tank. The norm is to have water in the EWH heated to maintain specific set temperature, which makes warm water available from the EWH at any time during the day, regardless of the users' consumption patterns. This results in excessive thermal losses into the environment, especially for users with lower usage (e.g. single shower once a day).

Standing losses refer to the energy lost due to heat dissipation from the water inside the EWH to the outside environment

as a result of the temperature difference. Standing losses can be modelled as a first order differential equation that describes the temperature decay toward the ambient temperature:

$$\frac{dT_{int}}{dt} = \frac{-AG}{cV_{ewh}} (T_{int} - T_{amb}) \quad (1)$$

Where: T_{int} is the temperature of the water in the EWH in degrees Kelvin; A is the surface area of the EWH that is exposed to the environment; G is the thermal conductivity of the EWH tank in $W/(Km^2)$; and T_{amb} is the temperature of the outside environment.

B. Inlet and ambient temperature (Seasonal variation)

Water that is withdrawn from the EWH is replaced with cold water from the inlet pipe. The temperature of this water determines the amount of energy lost by the tank as a result of a usage event. The balance of energy *lost* through a usage (or withdrawal) event (e.g. a bath or shower) is the difference of energy in the warm outlet water and in the the cold inlet. Put differently, the energy lost is the energy required to reheat the cold water to the same temperature as the volume of warm water that was used. The energy loss through usage over a sample interval is given by

$$E_{use} = cV_{use}(T_{int} - T_{inlet}) \quad (2)$$

where E_{use} is the energy in Wh , V_{use} is the volume used in litres, and the difference in temperatures in degrees Kelvin or Celsius. Inlet temperature values vary seasonally with soil temperature, however, the inlet temperature can be affected with a "preheating" phase, for example extended piping inside the house, or a preheating tank.

C. Contribution

This paper evaluates the impact of various energy savings actions for electric water heaters including: thermal blankets; pipe insulation; reduction in usage volumes; impact of ambient and inlet temperatures (seasonal and installation variations); reduction in set temperature; EWH tank size; use of schedule/optimised control. The paper uses various representative use cases for one- and three-person households - One person has higher portion of energy used by standing losses and three person has higher portion of energy consumption coming energy consumed by hot water usage events increases. Lookup tables are provided to cover various permutations.

The rest of this paper is organised as follows: section II describes related work in examining the impact of various energy savings actions on EWH energy consumption; section III describes the methodology used to determine the baseline energy consumption values and the development of the simulator used; section IV discusses the results of the simulations; and section V concludes the paper.

II. RELATED WORK

Fikru and Gautier [2] investigated the impact of weather variation on energy consumption for two residential houses with similar size and location in Tyler, Texas. One of the homes was a conventional house with advanced efficiency

TABLE I
AVERAGE DAILY ENERGY CONSUMPTION FOR VARIOUS SEASONS [2]

Season	Energy Usage (Wh)		Temperature
	House 1	House 2	
Summer	937.7	746.15	27.2°C (81°F)
Fall	911.7	588.8	16.1°C (61°F)
Winter	1558.3	1347.7	10°C (50°F)
Spring	761.97	720.7	21.1°C (70°F)

features (e.g. insulation in wall framing and high-efficiency compact fluorescent lighting) and the other was a net-zero solar house with additional efficiency features (e.g. high-efficiency and longer life light emitting diode lighting). They defined the units of heating and cooling degree minutes (HDM and CDM, respectively) which refer to the difference in temperature between an minute's average temperature and a given threshold temperature, which is considered to be a standard temperature that doesn't require heating or cooling (i.e. 70°F for heating and 76°F for cooling). Weather data and household energy consumption were logged at 5 minute intervals for approximately 16 months. During this time the houses were unoccupied and therefore no appliances were running, except the air conditioner, which was set to maintain a temperature of approximately 21°C (i.e. 70°F). Their results indicate that, on average, a 1°F increase in HDM results in an increased energy usage of approximately 9% and 5% for house 1 and 2, respectively. Similarly, a 1°F increase in CDM caused an increase of approximately 5% and 4% in the energy consumption of house 1 and 2, respectively. Additionally, it was found that the sensitivity of energy to use to weather depends on the season as well as the specific time of day or night. Furthermore, from the results of Table I, it is clear that the energy consumption of households varies significantly with the seasons.

Dutkiewicz [3] investigated the potential savings that can be achieved by various energy saving actions for EWHs based on the warm water requirements of typical middle income families in South Africa. This includes the impact of adding pipe and tank insulation in order to increase the thermal resistance of the system. The replacement of an EWH with an instant heater is also considered but is not considered optimum. This is because of the increased requirements of cabling and the installation cost of a 3-phase supply required to accommodate the increased wattage (21 kW) of the instant heater. Finally, Dutkiewicz highlights the importance of educating consumers on how to save energy for their EWHs (e.g. not running warm water unnecessarily or overfilling baths).

Bosman et al [4] investigated the impact of installing thermal blankets on the standing losses of standard EWHs in South Africa. The increased thermal resistance of the EWH reduces the standing losses of the device as heat is dissipated to the environment at a slower rate. The study included eighteen identical EWHs in a residential complex in Potchefstroom. Six of the EWHs were fitted with thermal blanked and periods where no warm water consumption occurred were used to determine the standing losses of the EWH. This data is then used to determine a linear approximation of the standing

losses as a function of ambient and set temperature. It was determined that the standing losses of these devices could be decreased by 18% on average. It was also found that reducing the set temperature of an EWH from 75°C to 55°C would result in twice the reduction on standing losses than installing a thermal blanket.

Gelažanskas and Gamage [5] analysed a set of hot water consumption data from residential households in order to forecast the hot water demand. The dataset consists of a 95 months worth of warm water consumption data obtained from 95 households, sampled in 1 hour intervals. Analysis of this data showed strong daily and weekly usage patterns for individual households but a wide variety of patterns between dwellings. Their results indicate that prediction methods can be used for DSM applications that are aimed at controlling EWH loads without compromising users' comfort.

Booyesen et al [1] examined the effect of implementing timer control which only heats water prior to usage for a typical 150 litre EWH. The usage profile is assumed to consist of one 75 litre warm water usage event every 12 hours. This would be the equivalent of almost 3 consecutive typical showers in South Africa [6]. The results of this analysis indicate that, even for the high usage profile assumed, the total energy consumption of the EWH can be reduced by approximately 15% if an efficient schedule is implemented. It should be noted that, although water heating should only occur before major usage events, enough water could be heated during these times to allow the EWH to still supply warm water for smaller usage events (e.g. washing dishes) that may occur in the interval between the major usage events.

III. EXPERIMENTAL SETUP

This section describes: the development of the baseline values of energy consumption for various usage profiles; and the parameters modelled by the simulations used in this paper.

A. Baseline Energy Consumption

In order to determine the baseline amount of energy consumed by EWHs, several usage profiles, shown in Table II, were created which include major warm water usage events (i.e. baths and showers). For profiles with 1 usage event, the event is assumed to occur at 06:00. For profiles with 2 usage events, the events are assumed to occur within 12 hours of one another. For example, profile 6 has one shower and one bath occurring once at 06:00 and 18:00, respectively. For profiles with 3 usage events, the 2 usage events are assumed to within 12 hours of one another, while the third usage event is assumed to occur with the first usage event at 06:00. For example, profile 6 has one bath and one shower occurring once at 06:00 and one shower occurring at 18:00. Profile 8 consists of 4 usage events and assumes one shower and one bath occur together at both 06:00 and 18:00.

A typical shower in South Africa consumes 59.1 litres of water in total [6], while a bath consumes . Furthermore, the desired temperature (i.e. mixed temperature) of the water at the shower outlet is typically 40.2°C [6]. This implies that the volume of warm water at 65°C required to create a typical

shower event is 26.53 litres. Based on the assumption that the amount of energy used by an event will remain constant for different warm water temperatures [7] and that water at the inlet temperature is at baseline energy [1]:

$$E_{usage} = m_{usage}c\Delta T \text{ [kWh]} \quad (3)$$

Where: E_{usage} is the total energy used by the event; m_{usage} is the mass of warm water consumed by the event; and ΔT is the difference in temperature between the inlet and set temperatures. Solving Equation 3:

$$E_{usage} = (26.53)(1.1611 \times 10^{-3})(65 - 20) = 1.39 \text{ kWh} \quad (4)$$

Therefore, a typical shower event can be assumed to consume approximately 1.39 kWh of energy. The amount of energy consumed by both usage events and standing losses for each of the profiles used for this analysis is summarised in Table II. The standing losses are calculated by assuming that the warm water in the EWH tank is at the nominal warm water temperature setting for EWHs in South Africa (i.e. 65°C) [8]. The amount of energy dissipated by standing losses was calculated using the simulator described in the following section.

B. Simulator Setup

A two-node physical model of an EWH, presented in [9], is used to simulate the thermodynamic response (and therefore energy consumption) of an individual EWH. This model was validated using consumption data from a household EWH which included x days and y usage events. The model is able to estimate the energy consumption of an EWH with an accuracy of 5 and 2 percent for thermostat and schedule control respectively.

The following values were used to establish the baseline energy consumption of an EWH for this analysis: 150 litre tank size; set temperature of 65°C; no pipe insulation or thermal blanket installed; regular thermostat control (i.e. heating allowed all day); and an inlet and ambient temperature of 20°C.

For the pipe insulation and thermal blanket variables, the thermal resistance of the system was increased by 6% [3] and 18% [4] respectively. For schedule control, the EWH started heating water 2 hours before the occurrence of a usage event and stopped heating 15 minutes before the usage event occurrence.

IV. RESULTS

The reduction in the total EWH energy consumption as a result of various energy saving initiatives is summarised in Figure 2. The results show that, in general, schedule control achieves by far the biggest saving, resulting in savings ranging from 9% to 16%. The biggest savings, as expected are the schedules where only one event occurs per day. The second most effective savings are achieved through insulation of the pipes and the tank, with savings ranging from 5% to 12%. From these results, it can be seen that initiatives that lower the standing losses of the EWH (e.g. schedule control) have the highest impact on profiles that have lower water usage (e.g. profiles 1 and 5). This is because the standing losses constitute a larger portion of the total energy consumed by the EWH

TABLE II
BASELINE ENERGY CONSUMPTION FOR TYPICAL USAGE PROFILES.

Profile #	Usage events		Energy consumption		
	# Showers	# Baths	Standing losses (kWh)	Usage energy (kWh)	Total energy (kWh)
1	0	1	2.577	1.876	4.453
2	0	2	2.572	3.752	6.324
3	1	1	2.575	3.262	5.837
4	1	2	2.555	5.138	7.693
5	1	0	2.581	1.386	3.967
6	2	0	2.579	2.772	5.351
7	2	1	2.558	4.648	7.206
8	2	2	2.538	6.524	9.062

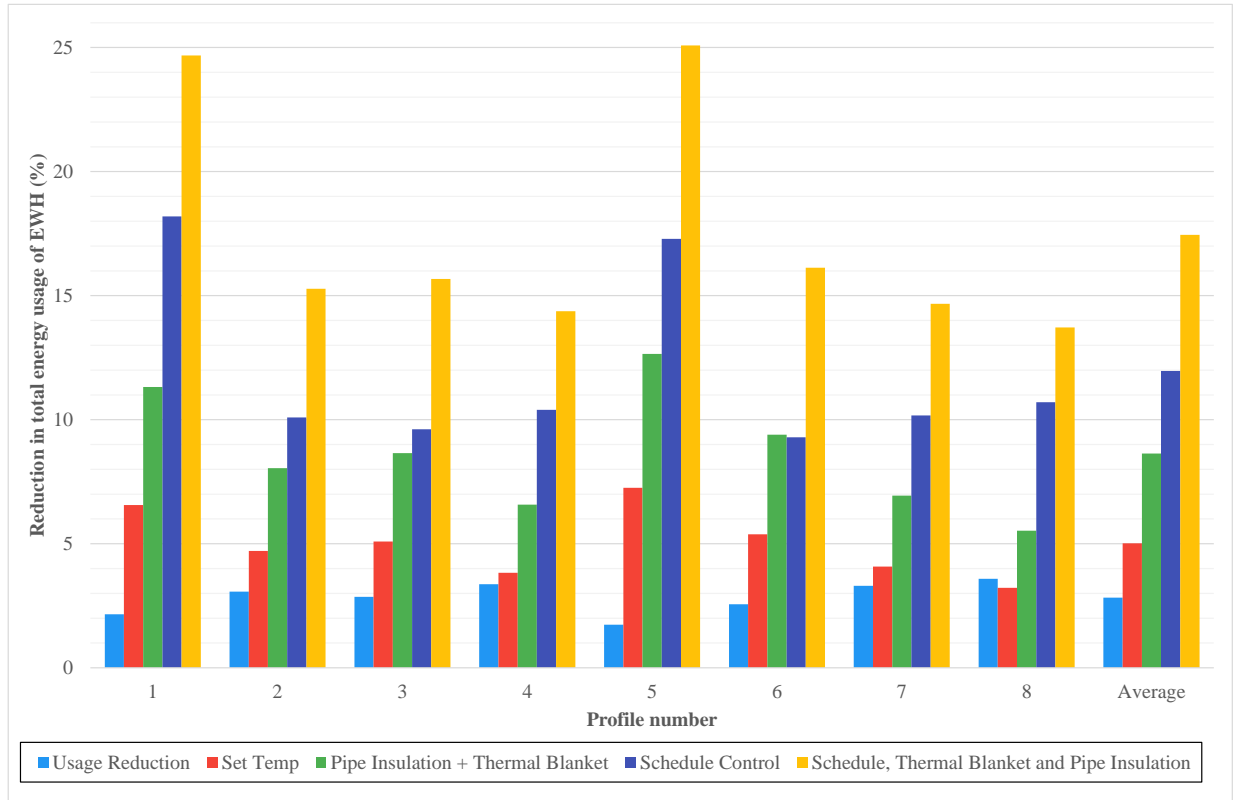


Fig. 2. Bar graph showing the reduction in the total energy consumption of an EWH for each profile shown in Table II as a result of: a 5% reduction in the volume of usage events (“Usage Reduction”); a 5°C reduction in the set temperature of the EWH (“Set Temperature”); the installation of pipe insulation and a thermal blanket (“Pipe Insulation + Thermal Blanket”); implementing schedule control to only heat water before it is required (“Schedule control”); as well as a combination of implementing schedule control and installing pipe insulation and a thermal blanket (“Schedule, Thermal Blanket and Pipe Insulation”). From these results, an average reduction of 17.45% can be achieved if schedule control is implemented in combination with the installation of a thermal blanket and pipe insulation.

for these low-use profiles. However, even for higher volume water usage profiles, such as profile 8 (which has 4 major usage events), the reduction in the total energy consumption as a result of reduced standing losses is still significant. For example, the total reduction in energy consumption as a result of implementing schedule control for profile 8 is 10.7%.

The effect of ambient temperature is important as device placement can have a significant impact on this variable. For example, if this device is placed outside on a roof, it would experience significantly lower ambient temperatures that if it were positioned in an attic area.

The impact of seasonal variations is illustrated in Figure 3 for the different consumption profiles. It is clear from these results that, despite the importance of ambient temperature, the

effect of the inlet water’s temperature is much more significant, except for profile 5, where a single shower occurs every day (i.e. very little cold water is let in). This shows that a mechanism where the inlet pipes are allowed to reach room temperature, or naturally pre-heated, before entering the EWH, will lead to significantly more savings than any change to the ambient temperature around the tank will have. Savings achieved through increasing the inlet temperature by a mere 5% leads to a reduction in energy consumed of more than 16% for the profiles where many big events occur (e.g. profiles 4 and 8).

The results of the simulations for various energy saving actions and seasonal variations in variables are summarised in Tables III and IV for single- and three-person households

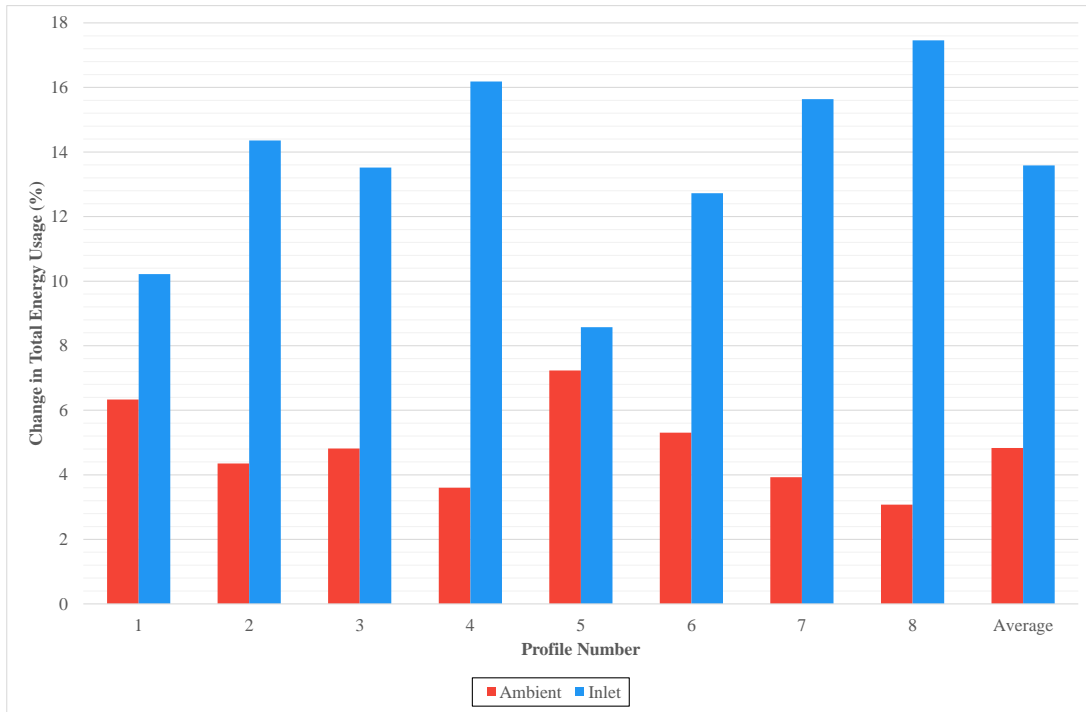


Fig. 3. Bar graph showing the increase in the total energy consumption of an EWH for each profile shown in Table II as a result of: a 5°C decrease in the temperature of the water entering through the inlet pipe (“Inlet”); and a 5°C decrease in the ambient temperature of the air surrounding the EWH (“Ambient”). From these results, it is clear that the inlet temperature has a significant impact on the energy consumption of the EWH, especially for profiles with higher usage volumes (e.g. profiles 4 and 8).

respectively.

A. Device Efficiency/Settings

From the results in Table III, the set temperature value of the EWH has a significant impact on the energy consumption for a single-person household. By simply decreasing the set temperature of the EWH by 5°C (to 60°C), a single-person household can achieve a similar total EWH energy reduction as reducing their warm water consumption by 20%. Furthermore, this same reduction can be achieved by installing a thermal blanket and pipe insulation. This is because the standing losses constitute a larger portion of the EWH energy consumption for lower occupancy households. Therefore, reducing the standing losses has a larger impact on the total EWH energy consumption for these households

The results in Table IV indicate that reducing the set temperature of the EWH by 5°C would result in the same reduction in EWH energy consumption as reducing the volume of water consumed by usage events by approximately 12% for a 3-person household. Additionally, this same reduction can also be realised by installing both a thermal blanket and pipe insulation on an EWH implementing thermostat control for a set temperature of 65°C. Furthermore, the results indicate that the inlet temperature has almost twice the effect on the energy consumption of the EWH for a three-person household than for a single-person household. This is as a result of the higher usage volumes from higher occupancy households, with a 5°C change in inlet temperature causing a change in approximately 15.7% of the total EWH energy consumption

for 3-person households (compared to 8.6% for single-person households).

Schedule control is efficient because it shouldn’t require any sort of behavioural change if implemented correctly. In other words, an effective schedule will be able to deliver hot water on demand while minimising the standing losses of the EWH.

For both single- and three-person households, the results indicate that schedule control has the most significant impact on the standing losses of the EWH. When schedule control, pipe insulation and a thermal blanket are implemented in combination the EWH energy consumption can be significantly reduced, resulting in total EWH average energy reductions of 25.1% and 14.7% for single- and three-person households respectively.

V. CONCLUSION

This paper evaluated the age-old question of how to best save energy used for household water heating. Various methods were evaluated, including changing the set temperature, reducing volume consumed, insulating the tank and the piping around it, and applying schedule control. These were compared using eight representative usage profiles. The results show that schedule control has the most significant impact on savings, saving as much as 18% for infrequent use profiles, and an average of 12% for all profiles. Thermal insulation saves as much as 12% for low-volume infrequent use, and an average of almost 9% across profiles. The results also shows that the temperature of the cold inlet water has a significant impact on energy consumption, with a 5% increase leading to

TABLE III

ENERGY IMPACT ANALYSIS RESULTS FOR ONE-PERSON HOUSEHOLD.

Variable	Value	Standing losses (kWh/day)	Usage energy (kWh/day)	Total EWH energy (kWh/day)	Total EWH energy (kWh/month)	Total HH energy (kWh/month)	Variable	Value	Standing losses (kWh/day)	Usage energy (kWh/day)	Total EWH energy (kWh/day)	Total EWH energy (kWh/month)	Total HH energy (kWh/month)	
Baseline	N/A	2.581	1.386	3.967	120.663	212.0	Baseline	N/A	2.558	4.648	7.206	219.182	579.0	
T_{set}	55°C	2.003	1.386	3.389	103.082	194.419	T_{set}	55°C	1.980	4.648	6.628	201.602	561.419	
	60°C	2.294	1.386	3.680	111.933	203.270		60°C	2.269	4.648	6.917	210.392	570.21	
	70°C	2.868	1.386	4.254	129.392	220.61		70°C	2.884	4.648	7.492	227.882	587.699	
$T_{ambient}$	10°C	3.155	1.386	4.541	135.385	229.459	$T_{ambient}$	10°C	3.126	4.648	7.774	236.459	596.277	
	15°C	2.868	1.386	4.254	129.392	220.730		15°C	2.844	4.648	7.492	227.882	587.699	
	10°C	2.575	2.072	4.647	141.346	232.683		10°C	2.523	6.949	9.472	288.107	647.924	
T_{inlet}	15°C	2.578	1.729	4.307	131.005	222.342	T_{inlet}	15°C	2.543	5.799	8.342	253.736	613.553	
	-5%	2.582	1.317	3.899	118.595	209.932		V_{usage}	-5%	2.562	4.417	6.979	212.278	572.095
	-10%	2.582	1.248	3.830	116.496	207.833			-10%	2.564	4.185	6.749	205.282	565.100
-15%	2.582	1.178	3.760	114.367	205.704	-15%	2.567		3.951	6.518	198.256	558.073		
-20%	2.583	1.109	3.692	112.298	203.635	20%	2.569	3.719	6.288	191.260	551.078			
Thermal blanket	N/A	2.187	1.386	3.573	108.679	200.016	Thermal blanket	N/A	2.167	4.648	6.815	207.290	567.107	
Pipe insulation	N/A	2.457	1.386	3.843	116.89	208.228	Pipe insulation	N/A	2.437	4.648	7.085	215.502	575.320	
Thermal blanket + pipe insulation	N/A	2.096	1.386	3.482	105.911	197.248	Thermal blanket + pipe insulation	N/A	2.076	4.648	6.724	204.522	564.339	
Schedule control	N/A	1.895	1.386	3.281	99.797	191.134	Schedule control	N/A	1.825	4.648	6.473	196.887	556.705	
Schedule control + thermal blanket + pipe insulation	N/A	1.586	1.386	2.972	90.398	181.735	Schedule control + thermal blanket + pipe insulation	N/A	1.501	4.648	6.149	187.032	546.850	
200 litre tank	N/A	3.016	1.386	4.402	133.894	225.231	200 litre tank	N/A	3.000	4.648	7.648	232.627	592.444	

TABLE IV

ENERGY IMPACT ANALYSIS RESULTS FOR THREE-PERSON HOUSEHOLD.

Variable	Value	Δ Standing losses (kWh/day)	Δ Usage energy (kWh/day)	Δ Total EWH energy (kWh/day)	Δ Total EWH energy (kWh/month)
T_{set}	55°C	-0.578	0.0	-0.578	-17.581
	60°C	-0.287	0.0	-0.287	-8.730
	70°C	+0.287	0.0	+0.287	+8.730
$T_{ambient}$	10°C	+0.574	0.0	+0.574	+17.459
	15°C	+0.287	0.0	+0.287	+8.730
	10°C	-0.006	+0.686	+0.680	+20.683
T_{inlet}	15°C	-0.003	+0.343	+0.34	+10.342
	-5%	+0.001	-0.069	-0.068	-2.068
	-10%	+0.001	-0.138	-0.137	-4.167
-15%	+0.001	-0.208	-0.207	-6.296	
-20%	+0.002	-0.277	-0.275	-8.365	
Thermal blanket	N/A	-0.394	0.0	-0.394	-11.984
Pipe insulation	N/A	-0.124	0.0	-0.124	-3.772
Thermal blanket + pipe insulation	N/A	-0.485	0.0	-0.485	-14.752
Schedule control	N/A	-0.686	0.0	-0.686	-20.866
Schedule control + thermal blanket + pipe insulation	N/A	-0.995	0.0	-0.955	-30.265
200 litre tank	N/A	+0.435	0.0	+0.435	+13.231

Variable	Value	Δ Standing losses (kWh/day)	Δ Usage energy (kWh/day)	Δ Total EWH energy (kWh/day)	Δ Total EWH energy (kWh/month)
T_{set}	55°C	-0.578	0.0	-0.578	-17.581
	60°C	-0.289	0.0	-0.289	-8.790
	70°C	+0.286	0.0	+0.286	+8.699
$T_{ambient}$	10°C	+0.568	0.0	+0.568	+17.277
	15°C	+0.286	0.0	+0.286	+8.699
	10°C	-0.035	+2.301	+2.266	+68.924
T_{inlet}	15°C	-0.015	+1.151	+1.136	+34.553
	-5%	+0.004	-0.231	-0.227	-6.905
	-10%	+0.006	-0.463	-0.457	-13.900
-15%	+0.009	-0.697	-0.688	-20.927	
-20%	+0.011	-0.929	-0.918	-27.923	
Thermal blanket	N/A	-0.391	0.0	-0.391	-11.893
Pipe insulation	N/A	-0.121	0.0	-0.121	-3.680
Thermal blanket + pipe insulation	N/A	-0.482	0.0	-0.482	-14.661
Schedule control	N/A	-0.733	0.0	-0.733	-22.295
Schedule control + thermal blanket + pipe insulation	N/A	-1.057	0.0	-1.057	-32.150
200 litre tank	N/A	+0.442	0.0	+0.442	+13.444

an average saving of 13% savings, compared to only 5% for the same change in ambient temperature.

ACKNOWLEDGEMENT

The authors would like to acknowledge: MTN for their continued support and funding through the MTN Mobile Intelligence Lab. Eskom for their financial support.

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