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Use of smart grid technology to compare regions and days of the week in household water heating

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M. Roux and M.J. Booysen

Abstract— Water heating is a leading cause of household energy consumption and, given its capacitive nature, has been the focus of research on demand side management and grid peak load management. Despite all the existing literature on energy for water heating, very little is known about an inextricably linked key determinant of it – demand for hot water and consumption patterns thereof. Moreover, even though water heating energy demand profiles have been investigated in the past, little is known about the different energy profiles for the days of the week, and regional variance of such profiles. This paper measures and reports actual hot water demand acquired through a novel smart metering solution. The different profiles for the days of the week are evaluated, in addition to weekdays and weekend days. Finally, differences between units in peri-rural Mkhondo and the urban Western Cape are compared in terms of water demand, energy demand, and efficiency (energy in vs. energy out). The results show a striking similarity to previous work, with the exception that scheduling has led to energy demand leading water consumption. The results also show that daily routines vary significantly, and also between regions. Surprisingly, the efficiencies and consumption patterns between the regions are also stark, with the urban Western Cape using 20 % more water on an average day, and with 70.2 % efficiency vs. 45.8 % in Mkhondo.

Index Terms— **electric water heating, hot water, smart grid, smart metering, Domestic energy consumption, domestic water consumption, demand forecasting, demand-side management, energy management, load modelling, load profile.**

1 INTRODUCTION

Energy crises are a recurrent concern for developing countries that experience capacity constraints and limited reserve margins. This is typically compounded by the fact that the peak demand periods of the residential load sector coincide with the peak demand periods experienced by the supply grid. This is further hindered by the large challenge faced in predictive modelling of residential load profiles.

South Africa has been plagued by the recurrence of energy crises in recent years, and more recently major water shortages in certain parts of the country have led to water rationing [1].

Opportunities for smart resource management solutions have arisen due to the increased energy and water concerns. Some key drivers that are required to provide the solutions are the accurate and high resolution measurement and logging of real-time demands of both power and water. Additionally, a user-friendly remote interface with real-time data reporting will increase user awareness with regards to their energy and water consumption habits within domestic settings.

Nationally it was found that the urban sector contributes up to 22 % of the water demand experienced in South Africa [2]. A significant contributor to the energy and water consumption of the residential sector is the ubiquitous electric water heater (EWH). The EWH is responsible for 7 % of South Africa's energy demand and 20 % of the residential energy demand. This figure has been seen to increase during peak hours to between 30 % and 50 % of the residential energy demand [3]. Furthermore, the EWH forms a nexus between residential energy and water demand, often only thought of when a consumer experiences unexpected cold water during a usage event.

Many myths have circulated on how to optimally manage and understand the EWH to provide economic benefits as well as preserve user comfort. Mainly the result is a consumer not knowing when to manually switch on the EWH, or for how long, to ensure lower energy consumption while still ensuring warm water on demand [4].

1.1 Contribution

This paper describes the results from a study that used the Smart EWH Controllers (SECs) described in [5] to measure household demand profiles for both electricity and water, creating a record for further analysis in a central database. These SECs were installed in households across South Africa with Mkhondo and the Western Cape forming the bulk of the installations. This paper provides an early investigation into the demand profiles of these two regions and presents some findings based on the different regions as well as day of the week between the two.

2 RELATED WORK

The methods of obtaining the data and controlling EWHs in this project have their roots from various precursor projects attempted by other teams. One of these precursors discussed a proof of concept [6], which introduced the scalability of connecting multiple EWHs to a central server via the internet. This concept allowed different institutions to remotely monitor or manage the energy consumption patterns of EWHs. However, the system presented in [6] makes no provision for capturing the volumetric consumption of water, which is critical for the analysis of consumer hot water consumption profiles. Furthermore, the communications infrastructure of the concept in [6] led to a data usage rate of

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1 MB per day, which was greatly improved with the implemented system of this paper which consumed only 5 – 7 MB per month. To facilitate the measurement and storage of all the EWH parameters, a novel solution was developed with the primary aim of providing a simple interface with which an EWH can be controlled and monitored. Furthermore, the solution aims to enable the discovery of household consumption patterns to provide insight into the ubiquitous but misunderstood EWH.

Considering the hardware available in literature, Brown *et al* [7] developed a smart EWH metering system that provides a user with an interface to control their EWH. The interface is presented in the form of a website which allows the user to control the water supply shut-off valve and the element state. The user is also able to set a heating schedule for the EWH. A limitation of this design is the communications infrastructure which takes place over Wi-Fi which is provided by the metering system. As such, a user must be in range to connect to the device with any Wi-Fi enabled device capable of displaying a webpage. Moreover, aggregated data is lacking.

Still at the hardware level, Nel *et al* [8] describe an inexpensive water usage detection system with an algorithm derived from the principles of Dolan *et al* Ref [9]. The fluctuations in outlet pipe temperature is used to identify the start and end of water usage events. Due to the lack of resolution of this method, it was only used to classify water usage events into small, medium or large events. Another limitation of this concept was due to the slow thermal decay of the outlet pipe which did not allow the estimation of either very small or successive larger water events.

Looking at the data processing side of the project, a computationally inexpensive energy model for horizontal EWHs with scheduling was used by [10]. This model simulates the internal temperature change resulting from energy extraction and input by means of hot water withdrawal and heating from the element, respectively. By providing a predetermined heating schedule along with water usage events, the model is able to simulate the amount of thermal energy output from usage events, electrical energy input from heating events and the energy lost from standing losses. By generating these figures the efficiency of the selected heating schedule for the predetermined water consumption pattern can be determined. The model consists of two versions: a one node model and a two node model which includes a thermocline. Although the model is discussed, no aggregated data is presented.

Investigations into the data produced by EWHs was undertaken by Booysen *et al* [11] where the impact of various heating schedules on individual savings was investigated by means of both lab and field experiments. The experiment consisted of setting the heating schedule of four participants aiming to reduce both the standing losses as well as the overall energy consumption. This provided insight into local consumption patterns and EWH management strategies with claimed saving of up to 29 %. Unfortunately, the scale of the experiment does not provide sufficient backing for the results.

In 1997, a large-scale DSM initiative was launched by Eskom to establish baseline data concerning electrical energy consumption throughout South Africa. One of the focal points was on water heating, which included residential EWHs. By utilising their “notch test” scheme over months of successive tests, Eskom determined the electrical demand profile of residential EWHs for weekdays, which can be seen in Fig 1. This provides insight into expected results for weekday power demand, however it does not make provision for regionality nor does it indicate hot water demand.

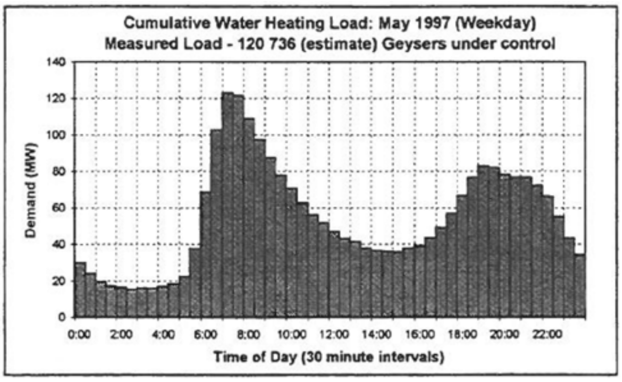

Fig. 1. Eskom notch test energy results from May 1997. Excerpt from [12].

3 EXPERIMENTAL SETUP AND DESIGN

The experiment was carried out with a system that consisted of pre-installed SECs connected to participants’ EWHs. The experiment utilised the logged real-world usage data of hot water and electrical energy of each participant. This data formed the basis of a usage profile for each participant. This section describes the experimental setup with a focus on the hardware, data limitations and data cleaning, and the profile of the actual participants.

3.1 System overview

The EWH of each participant is connected to the smart grid network physically by means of the SECs through a mobile network that provides a bi-directional communication layer between the outer nodes and the core system. Data is sampled once per minute, and stored and processed on an online database.

The frontend provides a simple yet informative depiction of the current state of the connected EWH for the user to interface with. This interface includes controls for the EWH, including setting the current heating mode to either ‘always on’, ‘always off’, a user-defined timer scheduled control and ‘auto’ schedule control which is based on the historic water consumption of the EWH. It was found that most users applied scheduled control.

3.2 Experimental Hardware Setup

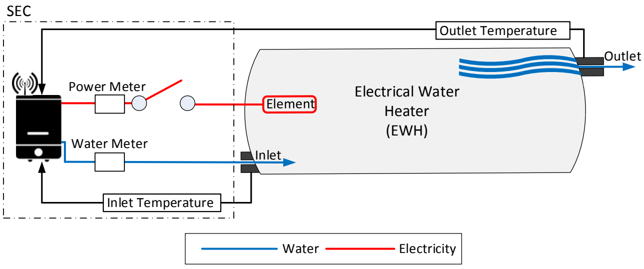

Fig. 2. SEC hardware setup [5].

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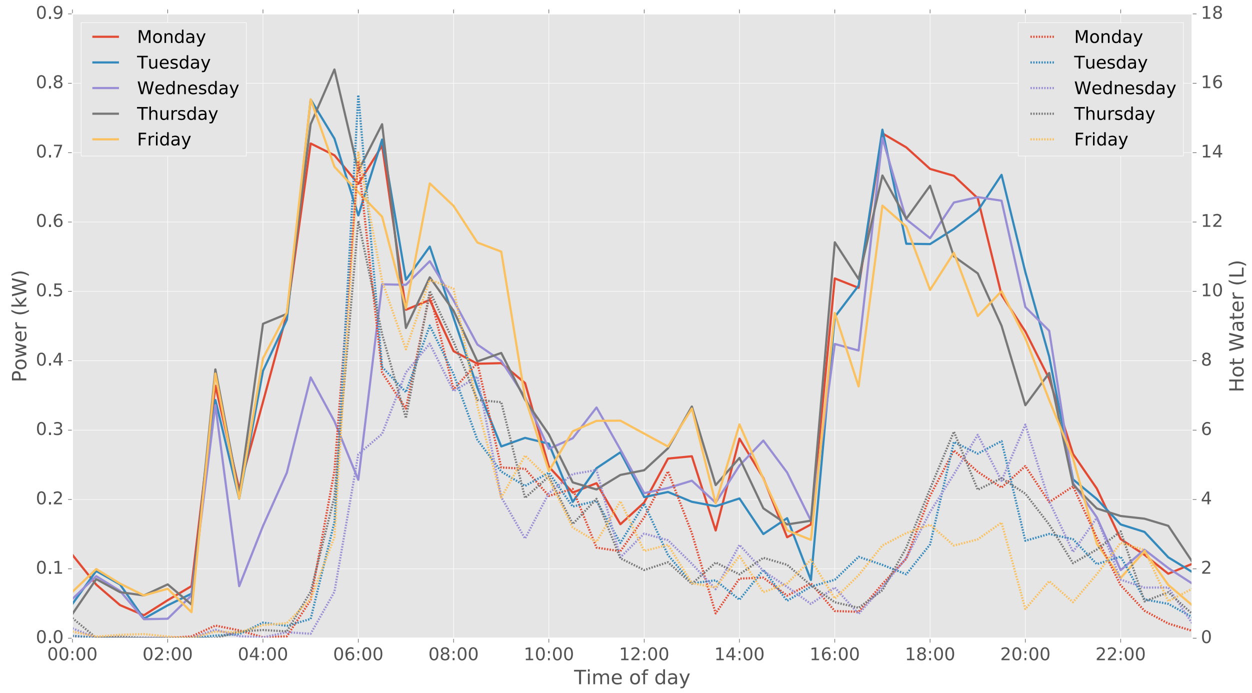

Fig. 3. Normalised cumulative power and hot water consumption for all units from Mkhondo and Western Cape for each weekday.

The sensing and actuation of the EWH setup is shown in Fig 2. The electrical supply of the EWH is intercepted and controlled by the SEC. The parameters that determine when the relay should toggle is determined by the current temperature and user- or scheduled control instructions received from the server. The power delivered to the heating element is continually measured, along with the water usage and reported to the server. Finally, the inlet and outlet temperatures are measured to provide an additional dimension of control and enable the calculation of thermal energy levels contained in the water within the EWH at a minutely resolution.

3.3 Experiment Parameters, Limitations and Reach

A period of 4 weeks was selected to provide sufficient insight into trends from users in varied households during regular usage. Due to various challenges that relate to connectivity and user behaviour, the data from many of the EWHs had to be discarded to ensure data integrity, and a total of 35 EWHs were used for the analysis.

Mkhondo and the Western Cape were the two most prominent regions in which the dataset had a sufficiently high level of integrity. This provides the opportunity to compare users in a rural setting with that of users in an urban setting. The distribution of the SECs by region are: Mkhondo with 18 units and the Western Cape with 17 units.

A previously assumed bias of routine was hypothesised which would be a separation factor between the usage patterns of weekdays and weekends. Due to the demands of work and other scheduled responsibilities that follow during the weekday, a hot water demand profile with peaks in the mornings and evenings were expected. The same conjecture was not made for weekends, with a more unpredictable nature expected as users took time to relax and be free from their strenuous weekday schedules.

Due to the capacitive nature of EWHs, the energy is not used instantaneously, but rather it is stored in the water as heat, which is then used by the consumer. This means that energy transferred into the water in the evening is not necessarily utilised in the evening and may carry forward into the morning, reducing the required amount of additional energy required in the morning to sufficiently increase the temperature of the hot water for morning usage. The same applies for excess hot water from the mornings carrying over to the evenings. This transfer of stored energy is not considered during morning and evening energy consumption, under the assumptions that firstly each evening transfers some energy to the morning and the morning to the evening, and that secondly the regularity of the days ensures similar amounts of energy to be transferred during the night and day times. The delivered thermal energy in the water is calculated by:

$$\boldsymbol{E_{water} = c_p m \Delta T} \qquad (1)$$

Where:

E_{water}	thermal energy contained in the water;
c_p	specific heat capacity of water;
m	mass of the water;
ΔT	difference in outlet and inlet water temperatures

For the case of the domestic EWH the specific heat was used as 4.186 kJ / (kg K). To calculate the mass, an assumed constant density of water was selected of 1 kg / L, due to little relative variance at various temperatures expected in an EWH.

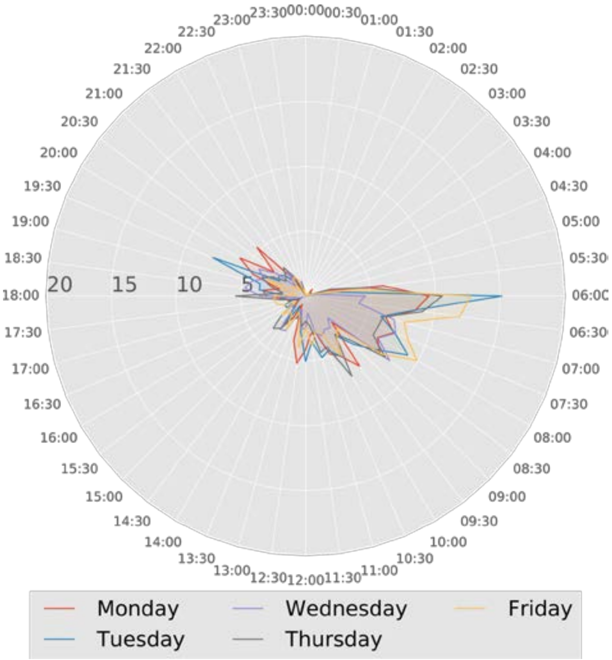

Fig. 4. Normalised hot water consumption for all units from Mkhondo for each weekday in L.

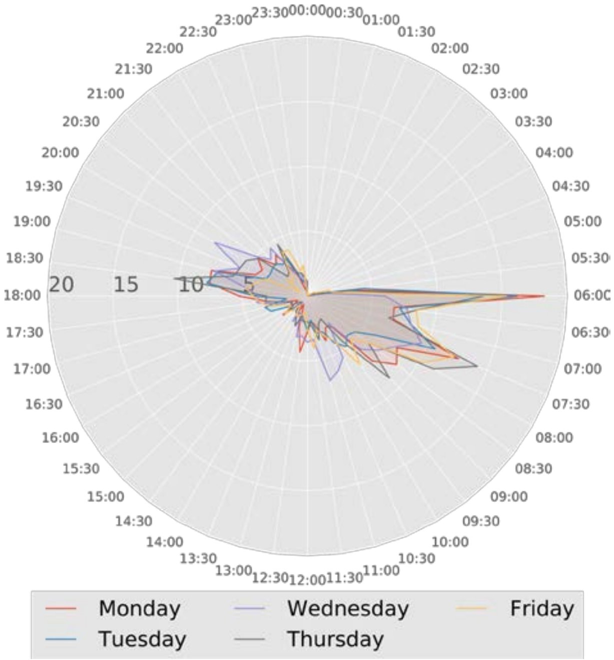

Fig. 6. Normalised hot water consumption for all units from the Western Cape for each weekday in L.

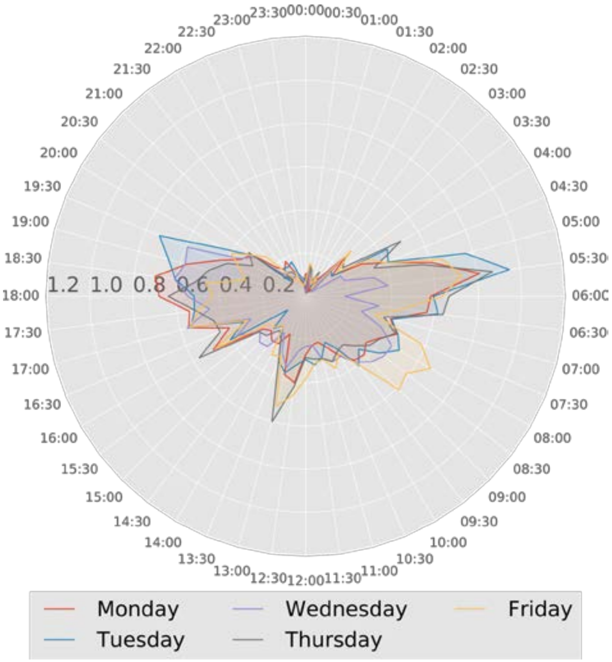

Fig. 5. Normalised power demand for all units from Mkhondo for each weekday in kW.

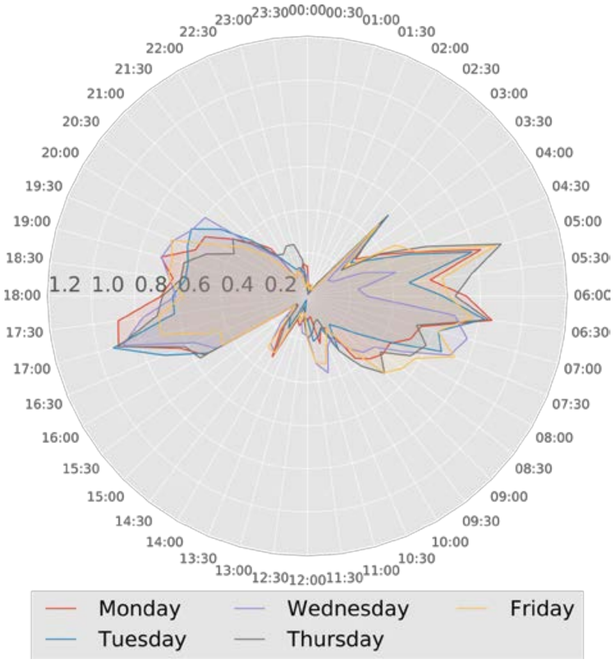

Fig. 7. Normalised power demand for all units from the Western Cape for each weekday in kW.

4 RESULTS

4.1 Electricity and Hot Water Weekday Demand

Fig 3indicates a familiar distribution of cumulative water heating load per each weekday for all SECs in the set, like Fig 1, whereby there are evident peaks in the mornings and evenings. The morning hours still report a relatively narrow period of power demand, leading to the maximum peak of the day. It is however evident that since 1997 people have been making more effective use of their EWHs – It is clear that the energy peak has shifted earlier due to scheduling, admittedly for a group that could represent self-selection bias given the profile of an early adopter. This shift is evident in the proactive nature of the usage distribution, with the power demand leading the hot water demand, in the morning by an hour on average and two hours in the evening on average. Contrasting Fig 3 with that of Fig 1, it is also evident that hot water usage period in the mornings have remained the same, evident by the hot water usage in this study and from a reactive power demand back in 1997, with the highest hot water demand being at 06:00 in the mornings.

Looking at the evenings, it is evident that the power demand forms a much broader period of usage, indicating the after-hours schedule of users is not as structured and scheduled as in the mornings. This is further supported by the logged hot water usage which only starts picking up at just after 18:00, continuing until 21:00. A seeming outlier to this

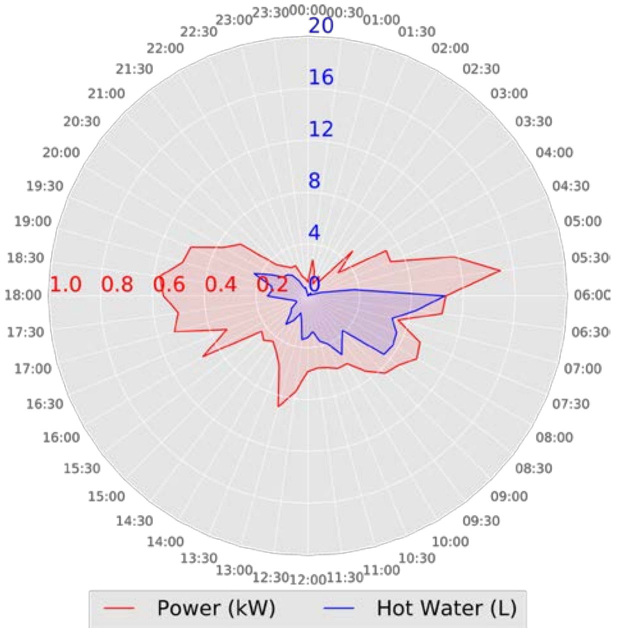

Fig. 8. Normalised hot water consumption and power demand for Mkhondo on an average weekday.

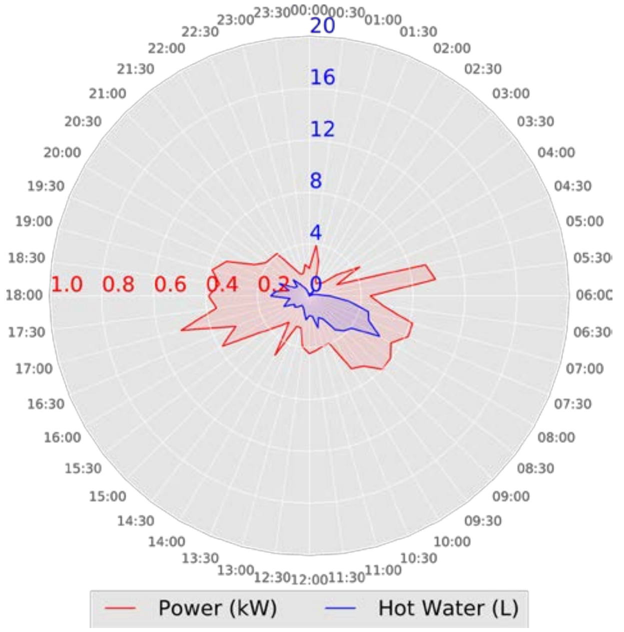

Fig. 10. Normalised hot water consumption and power demand for Mkhondo on an average weekend day.

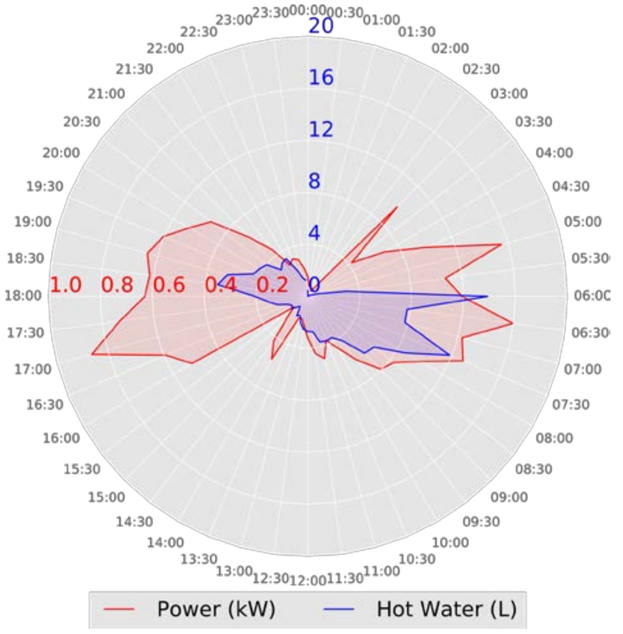

Fig. 9. Normalised hot water consumption and power demand for the Western Cape on an average weekday.

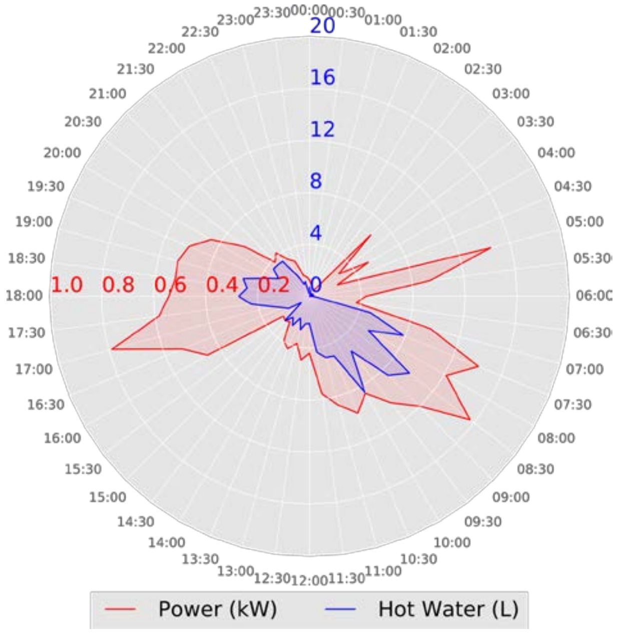

Fig. 11. Normalised hot water consumption and power demand for the Western Cape on an average weekend day.

trend of hot water usage in the evenings is Friday, with the average usage almost half of the expected value and a clear increase in hot water demand just after 22:00, unique to Friday evenings. The lower demand could indicate either a regular social event on Friday evenings, supported with the much later than usual, after 22:00 increase.

Fig 4, Fig 5, Fig 6 and Fig 7 provide a higher resolution picture of the usage patterns of users from Monday to Friday for a direct comparison of the power and hot water demand between the two regions. Starting off with Mkhondo, from Fig 4 it is evident that the largest amount of hot water is used during the mornings, and typically starts off at 06:00 with a broad period sweeping over until 08:30. From Fig 5 it is evident that the power demand is proactively scheduled to accompany this for all these work days. The hot water and power demand tapers off for the rest of the day, except for Fridays which have the highest morning water and power demand of all these days, with the later hot water demand being reactively heated by the EWH from 07:30 until 09:00. Over the expected lunch time there are some hot water usage event which are again reactively replenished as indicated by the apparently scheduled power spikes at 13:00, most notably are Thursdays and Fridays which have the highest spikes during this time. Coincidentally, Thursdays and Fridays also report the lowest hot water demand during the evenings. Of particular note is the anomalous demand profile of Wednesday mornings, with a delayed hot water demand, leading to a delayed power demand. The shift is evident as the peak hot water demand has shifted from the typical 06:00 to 08:30. This delay in morning hot water usage could indicate special arrangements for work on Wednesdays such as working at home or possibly work starting later as this was observed to be a regular occurrence.

Similarly, The Western Cape demand profiles look similar for each day of the week, as seen in Fig 6 and Fig 7. In contrast with Mkhondo, however, the Western Cape demand profiles are more specific to mornings and evenings, forming an almost mirror image for both distributions, with little hot water and power demand during the day. Interestingly, Fridays again show a decreased hot water demand during the evenings, possibly due to social events or simply postponing hygiene until the weekend has started. Furthermore, Wednesdays again show anomalous trends as the typical peak of hot water usage has been shifted from 06:00 until 07:30, which is in line with the secondary peak of all the other days, with its own secondary peak only showing up at 11:00. From the power demand, it is evident that more scheduled control is utilised by the Western Cape consumers with many prominent spikes occurring throughout the mornings and evenings, most notably at 03:00, 05:00, 06:30, 16:00 and 17:00.

4.2 Weekday vs Weekend Demand

As discussed earlier, weekdays tend to share a similar trend and as such were investigated separately from weekends. A normalised cumulative distribution of the power and hot water demand was considered for both weekdays and weekends, separated by region. This will provide insight into the differences between the daily habits of the two regions of Mkhondo and the Western Cape.

Firstly considered are weekdays in Mkhondo: Looking at Fig 8 it is evident that in the mornings and evenings the power demand leads that of the hot water demand, in other words, a proactive heating pattern. Contrast this with the reactive usage pattern where the power demand lags the hot water demand during the day. Of specific interest are the two peaks of hot water usage in the mornings, at 06:00 and at 08:30. This could indicate the different lifestyles and work schedules of consumers in various households, but potentially also that of consumers sharing a household. Comparing this with the weekday demand of the Western Cape in Fig 9, it is evident that the Western Cape has a power demand that follows the hot water demand much closer, an almost purely proactive usage pattern. The peaks of power demand all tend to coincide across all the EWHs, leading to clear peaks in the mornings at 03:00, 05:00 and 06:30 and in the evenings at 16:00 and 17:00. This is a clear indication of common times for scheduling, which would imply significant load peaks on the grid for large-scale deployment. In terms of hot water usage, two clear peaks are yet again visible, however both falling within a shorter period, the first at 06:00 as in Mkhondo but the second at 07:30, a full hour before the equivalent secondary peak in Mkhondo. This is a clear indication of the effect of urbanisation, where all people in the household tend to have work schedules earlier in the mornings. And furthermore, it indicates two different classes of workers, with some starting the day earlier than others, possibly due to long commute periods or working at home.

Table I. Comparison of normalised weekday vs weekend energy and hot water consumption in **Mkhondo**.

Days	Time	E In (kWh)	E Out (kWh)	**Losses (kWh)**	η (%)	Hot Water (L)
Weekday	AM	4.0	2.3	1.7	57.3	85.9
	PM	4.0	1.4	2.6	34.4	54.5
Total		8.0	3.7	4.3	45.8	140.4
Weekend	AM	3.0	1.3	1.7	43.7	47.6
	PM	3.0	1.0	2.0	34.6	39.7
Total		6.0	2.3	3.7	39.1	87.3

Table II. Comparison of normalised weekday vs weekend energy and hot water consumption in **Western Cape**.

Days	Time	E In (kWh)	E Out (kWh)	**Losses (kWh)**	η (%)	Hot Water (L)
Weekday	AM	4.2	3.4	0.8	79.5	92.6
	PM	4.3	2.6	1.7	60.8	76.9
Total		8.5	6.0	2.5	70.2	169.5
Weekend	AM	4.1	2.8	1.3	66.9	74.5
	PM	3.8	2.5	1.3	66.1	73.7
Total		7.9	5.3	2.6	66.5	148.2

The shape of the profiles of the two regions differ somewhat and prompts the question, which is more energy efficient? From Table I, with focus on the weekdays, it is observed that the power demand is evenly split between the mornings and evenings, however most hot water is extracted in the mornings. This leads to a reduced efficiency of the EWH as a larger portion of the energy contained in the EWH is radiated out of the EWH as heat, rather than being used by the consumer. This is evident in the overall morning efficiency of the EWH being 22.9 % higher than in the evening. Contrasting this with the Western Cape in Table II, which has both a higher power demand in the mornings and evenings, 6.0 % and 7.0 % higher respectively, and higher hot water demand, 7.8 % and 41.1 % higher respectively. However, even though the overall consumption is higher in the Western Cape, the efficiency of the EWH is significantly higher in both the mornings and evenings, with 57.30 % vs. 79.58 % for AM, and 34.40 % vs. 60.81 % for PM. As such, Western Cape consumers have a much higher energy output for a similar energy input.

Looking at the weekends, the overall profile of the consumption follows the same trend, power and hot water demand is more typically present in the mornings and evenings, albeit not as high.

In Mkhondo, the hot water consumption in the mornings tend to take place later, with the peak shifting from 06:00 during weekdays, to 08:00 during weekends. This is not a very large shift, but indicates the Mkhondo consumers have established routines over weekends which prompt them to not sleep in too late. This indicates that the potential of accurately predicting weekend usage patterns is higher than previously assumed. Furthermore, the power demand indicates spikes which are indicative of scheduling at 04:00, 05:00, 05:30 and 17:00, potentially from consumers setting roughly the same

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schedule for weekends as each day of the week, with the condition that they will only change it if they experience cold water.

The same can be said for Western Cape consumers, with their first hot water demand peak shifting from 06:00 to 08:30, and the second from 07:30 to 10:00. Looking at the power demand peaks, the first two have remained the same, namely 03:00 and 05:00, with a more evident 04:00 scheduling group showing up over the weekends. The next morning peak however has shifted from 06:30 to 07:30, again indicating a set routine ingrained in the consumers. However, one of the highest peaks of the day occur at 08:30, indicating that more people tend to sleep in over the weekends. It is important to note that the weekend power demand takes on a more reactive usage pattern, which could be explained by people leaving their EWHs on over the weekend after the initial activation in the morning. Considering the evenings, it is interesting to note that the power demand profile almost exactly mirrors that of the weekday evenings, with schedules being set at 16:00 and 17:00, although at a reduced amount. The overall hot water usage takes place over the same period, however it is seen that the peak is more spread out and overall usage is less.

With the weekend profile shapes of the two regions correlating rather well with that of the respective weekday profiles, a closer inspection of the figures provides some interesting insight. Starting with a weekday and weekend comparison of Mkhondo, from Table I, it is evident that the energy demand decreases significantly for weekends, 23.9 % in the mornings and 25.2 % in the evenings. This is further augmented by the accompanying decrease in hot water usage with a reduction of 44.6 % and 27.2 % in the mornings and evenings respectively. With the decrease in both energy and hot water demand, the overall efficiency of the EWH has gone down by 23.8 % in the morning and increased by only 0.5 % in the evening. This means that over weekends there is lower consumption overall, but the efficiency of this reduced amount has also been lowered. This weekend reduction is possibly as a result of the migrant workers in the Mkhondo area, returning home over weekends.

A similar trend is observed of lower overall consumption in the Western Cape, albeit a smaller change. The energy demand decreases by 1.9 % in the mornings and 11.0 % in the evenings, along with the hot water demand by 19.5 % and 4.2 % for mornings and evenings respectively. These figures are not as significant as the decrease shown by the consumers in Mkhondo, however the Western Cape EWHs experience less of a change in the overall efficiency, with 15.9 % decrease in the morning and an increase of 8.74 % reported for the evenings. From these results, it is evident that the Western Cape EWHs are operated more efficiently over weekends than weekends in Mkhondo. Overall average daily efficiency of EWHs in Mkhondo is a mere 45.8 %, while in the Western Cape it is 70.2 %.

From this it can be concluded that Western Cape EWHs are operated at higher efficiency overall, with a peak efficiency being reach during weekday mornings, although they consume more energy and water overall.

5 CONCLUSIONS AND RECOMMENDATIONS

The system with its relatively new infrastructure provided a good means to obtain the resulting data for mining. The minutely resolution of the data provides a high level of resolution at minimal data cost which adds to the feasibility of the solution. Looking at the data, the two regions, Mkhondo and the Western Cape, provided a great first impression of the knowledge that can be gained from the data. Mkhondo is observed to be a more rural setting from the usage patterns and having a more lagging power demand. This lead to low efficiency EWH usage, especially in the evenings. Contrasting with the Western Cape, a typically more urban setting, which showed a marginal increase in energy demand but a significant increase in hot water demand, managed to utilise effective scheduled control to provide a great improvement to EWH efficiency both in the mornings and evenings. The resolution of the data furthermore provided insight into EWH usage over weekends, providing the interesting depiction that usage profiles do not differ much from weekdays, albeit with lower demand overall. As the technology matures and becomes part of the daily routine of all users, large economic benefits may result as users take control of their usage due to the awareness. This will also provide great insight in the long term to seasonality changes in user demand profiles.

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