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Evaluating the impact of consumer behaviour on the performance of domestic solar water heating systems in South Africa

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Pamela Ijumba
Eskom, Megawatt Park, and the Department of Electrical Engineering, University of Cape Town

Adoniya Ben Sebitosi
Centre for Renewable and Sustainable Energy Studies, University of Stellenbosch

Abstract
South Africa experienced a rapid expansion in the electric power consumer base after 1994 that was not matched by corresponding investment in the country's generation capacity. By the dawn of 2008, the situation had reached a critical point, with regular countrywide blackouts and load shedding and is expected to persist for several years, before the proposed new base stations can come online.

Currently, 92% of the country's electricity is generated in coal-based power stations and are responsible for the country's heavy carbon footprint. Additionally this power must crisscross the country to distant load centres via an aging transmission infrastructure and in the process massive amounts of energy are lost particularly during peak power demand.

Electricity consumption in South African households accounts for approximately 35% of peak demand, with water heating constituting 40% of that. The country has abundant sunshine and solar water heating technology and offers one of the most viable compiementary solutions to the country's energy and environmental crises. Moreover the location of the systems at the consumer end means that the need to upgrade the transmission infrastructure can also be differed.

Application of technology alone however, may not necessarily result in the required energy savings particularly in cases of uninformed consumer usage. In this paper the authors evaluate the impact of consumer behaviour on the performance of domestic solar water heaters in South Africa and suggest measures that could be taken to optimize this performance.

Keywords: Solar water heating; consumer behaviour; South Africa

Nomenclature

Acronyms

EDHW	Electric Domestic Hot Water
SDHW	Solar Domestic Hot Water
EHW	Electric Hot Water
SHW	Solar Hot Water

Symbols

I	Current (A)
R	Resistance (Ω)
P	Power (W)
V	Voltage (V)
T	Temperature (°C)
η	Efficiency
Q	Energy (J or Wh)
A	Area (m^2)
IT	Incident Solar Radiation (J/m^2 or Wh/m^2)
m	Flow rate (m^3/s)
C	Specific Heat (J/g.°C)
ρ	Density (m^2)
V	Volume (m^3)
P	Pressure (Pa)
g	Gravitational Constant (m/s^2)
h	Height (m)

1. Introduction

1.1 Background

South Africa has, in recent years, experienced high economic growth as well as a rapid expansion in the electric power consumer base. As a result, the demand for electricity has escalated but has not been matched by corresponding investment in generation. At the dawn of 2008 the situation had reached a critical point, with regular countrywide blackouts and load shedding. These have been predicted to persist for several years, before the proposed new base stations could come online.

Currently, 92% of the country's electricity is generated in coal-based power stations, which are situated in the coal-rich North-eastern regions and is responsible for the country's heavy carbon footprint. This power must crisscross the country to distant load centres via an aging transmission infrastructure and in the process massive amounts of energy are lost particularly during peak power demand and thus exacerbating the reliability problem even further.

Electricity consumption in South African households accounts for approximately 35% of peak demand, with water heating comprising 40% of that (EDRC, 2003; DEAT, 2004). Solar energy is widely available in South Africa and the country's utility and policy makers have proposed domestic solar water heating as one of the most viable complimentary solutions to the country's energy and environmental crises.

Application of technology alone however, may not necessarily result in the required energy savings particularly in cases of uninformed consumer usage (Sebitosi & Pillay, 2007). In this paper, the authors evaluate the impact of consumer behaviour on the performance of domestic solar water heaters in South Africa and suggest measures that could be taken to optimize performance.

1.2 The energy conservation hierarchy

The Institute of Engineering and Technology (IET) has developed an Energy Conservation Hierarchy, shown in Table 1, which is included in their Primer on Energy Policy (IET, 2007). It aims to promote sustainable development by focusing on consumer behavioural change as the first line of action in reducing energy usage. This is the most cost effective conservation measure, as it requires no capital investment and no timelines. It is followed in hierarchy by the use of energy efficient appliances and then followed by use of clean power generation methods. The use of traditional methods of energy production is only recommended as the last option.

Table 1: The IET energy hierarchy

Source: Institute of Engineering and Technology, 2007

Sustainable	Energy conservation Changing behaviour to reduce demand
↑	Energy efficiency Using technology to reduce demand
	Renewable, sustainable energy sources Setting a course to replace fossil fuels
	Conventional energy sources Using low/no-carbon technologies
Unsustainable	Exploitation of Conventional Energy Sources

The installation of solar water heating satisfies the 2nd and 3rd levels of the hierarchy. However, as will be illustrated in this paper, different consumers may realize varying savings from identical installations (even when the weather conditions are the same) depending on behavioural differences.

2. Research methodology

The performance of a solar water heating system is dependent on factors such as system location, orientation, tank-size and water usage pattern. In South Africa, these systems are still expensive; it has thus become necessary to find a means to determine the savings that the installation of a SWH system will bring about, prior to investment by the customer and the utility.

2.1 Software programmes

South Africa consists of several different climates that range from Cape Town's Mediterranean cool, wet winters; Johannesburg's dry climate; the Karoo's dry winters and the East Coast's subtropical warm winters and sultry summers (Travel.Net, 2007). These do impact on the performance of an installation. It would, therefore, be important to predict the expected performance of these solar water heaters at the various locations around the country.

Trying to achieve this through monitoring pilot installations countrywide could, however, prove to be prohibitively expensive and perhaps endless. Thus the authors employed computer simulations for the larger part of this study. MeteoNorm and TRNSYS are two software packages that were used in this regard (Remund & Kunz, 2003; Transys.com). Then, in order to try and validate these results, a sample of households in Cape Town was subsequently selected and monitored for six months.

2.2 Water consumption profile

The electricity consumption profile for water heating is dependent on the time of hot water usage, and this varies from individual to individual. The typical South African hot water consumption profile (Harris et al., 2007; Meyer & Tshimankinda, 1997), depicted in Figure 1 was used as the water draw profile for the simulations.

2.3 Trnsys simulations

In order to determine the impact of a solar water heating system on electricity demand, a comparison needed to be carried out between a water heating system that used electricity only (Electric Domestic Hot Water System – EDHW), and one that had an additional solar water heater installed (Solar Domestic Hot Water System – SDHW). Thus two simulations were done for each location; one for an EDHW system and one for an SDHW system.

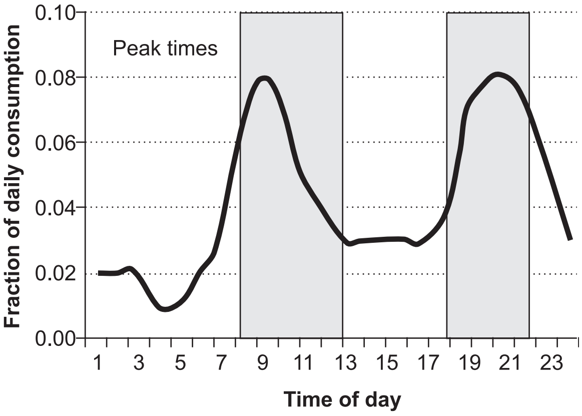

Figure 1: Typical South African hot water consumption profile
Source: Meyer & Tshimankinda, 1997

2.4 Simulation parameters and set up

The systems simulated in TRNSYS had parameters as set out in Table 2. The values were extracted from literature, and are typical values for an average South African household.

Table 2: Simulation system parameters

	SDHW system	*EDHW system*
Collector area	2m^2	-
Intercept efficiency	0.706	-
Efficiency slope	4.9099W/m^2.K	-
Tested flow rate	70kg/hr.m^2	-
Collector slope*	30°	-
Tank volume	200l	200l
Tank height	1.5m	1.5m
Thermal conductivity	1.5kJ/hr.m.K	1.5kJ/hr.m.K
Overall loss co-efficient	5kJ/hr.K	5kJ/hr.K
Geyser element rating	3kW	3kW
Thermostat setting	65°C	65°C

** It is recommended that the collector slope is equal to the latitude of the chosen location. The cities chosen lie between 24°S and 33°S thus a slope of 30° (typical roof angle) was chosen. It was verified that this did not adversely affect the simulation results.*

The systems for simulation in TRNSYS were set up. A 'Weather' component allows for the input of the various climate data files generated by MeteoNorm, and a 'Water Draw Profile' is a link to the water consumption profile. A tee-piece and the diverter form a mixer circuit for hot and cold water. 'Type 45a' is the model for the thermosyphon solar collector, and 'Type 38' is a model for an electric geyser. These are in conformity with the specifications of the components used in South Africa.

The output studied was the geyser's electricity demand curve. Simulations were carried out using a time step of 15 minutes, over a period of one year. This yielded over 30 000 data points for each simulation. In order to analyse the data, average monthly geyser demand curves were compiled for each month of the year, for every simulation. A comparison was then carried out between the EDHW geyser demand and SDHW geyser demand curves, in order to establish the impact of a SDHW system on peak demand.

2.5 Monitoring of solar water heating installations

Another part of the research involved the monitoring of solar water heating systems that had been installed in a number of households around Cape Town. This was done with the help of Atlantic Solar (Pty) Limited, a Cape Town based company that deals with the design, manufacture and installation of solar water heating systems.

Atlantic Solar agreed to install data loggers at their installations. A simple schematic of the set up of the logging equipment is shown in Figure 2. These loggers were used to record the geyser's hourly electricity (current) consumption as well as the household's hot water usage. This data was then used to compile average monthly geyser demand curves and water consumption profiles.

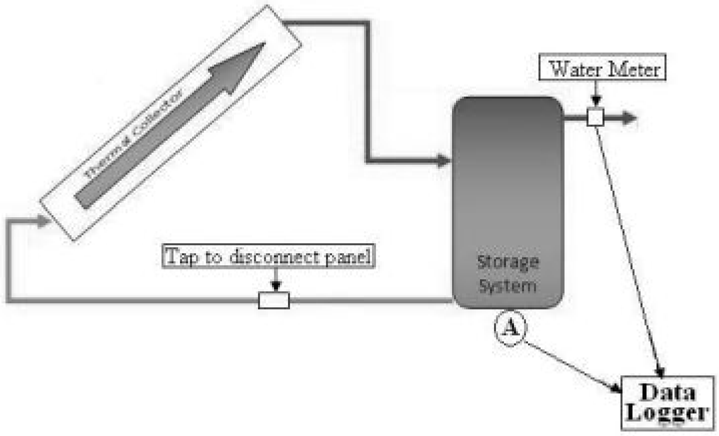

Figure 2: Set up of data logging equipment

As can be seen in Table 2, a tap was included during the installation, which allowed for the panel to be disconnected. This would allow the external solar water heaters to be connected or disconnected from the geysers. Every alternate week the tap was connected and disconnected the following week. This routine was important in order to normalize the effects of weather on the performance of the system by comparing adjacent weeks. The data obtained during these periods would subsequently be used to create EDHW curves that allowed for comparison, to assess the impact of a SDHW system on peak demand.

The data collected from the Atlantic Solar SDHW system installations was compared to the simulation results from TRNSYS, in order to validate the accuracy of the TRNSYS models, as well as the climatic data created by MeteoNorm.

Once the simulation results were validated, they were analysed, in order to quantify, as a percentage, the change in household electricity consumption during peak demand times, due to the use of a SDHW system. These peak demand reduction factors were then used to find out if solar water heating would have any effect on the transmission grid.

3. Suggested consumer behavioural changes and results

3.1 Using a cooler shower

Geyser thermostats control the heating element's activity. If the water temperature in the tank falls below a certain threshold, the element will be turned on, until it reaches a desired level. In South Africa, thermostats are normally set at around 65°C. If the thermostat setting was reduced, less electricity would have to be used to heat the water and thus higher energy savings could be achieved. This includes the additional fact that hotter water creates a higher temperature gradient with the ambient which increases the rate of heat loss.

A scenario where the thermostat was set to room temperature (25°C) yielded great energy savings as can be seen in Figures 3 to 5. However, this would obviously, not be ideal for the consumer. Not only would the setting mean a cold shower, it would also allow certain harmful bacteria, like Legionella to survive in the geyser (Travel.Net, 2007).

A reduction of 5°C or even 10°C of the thermostat setting (from the default 65°C) on the other hand, is still sanitary and does not compromise the consumers' comfort (Mr Chris Wozniak, a Technical Officer in the Department of Electrical Engineering, has reduced his household's thermostat to 55°C and has found the water temperature to be acceptable). This small reduction can bring about increased energy savings as illustrated in Table 3.

The SDHW system geyser demand curves for 65°C, 60°C and 55°C thermostat settings all have a similar shape. However, the energy consumption differs for each scenario. The monthly energy consumption for each scenario, as well as the energy savings as compared to the original SDHW system are shown in Table 3. The figures in brackets correspond to the savings as compared to the original SDHW system. The annual energy consumption of each system is also included.

Based on the annual figures presented in Table 3, reducing the thermostat to 60°C can increase SDHW system energy savings by approximately 3%, and reducing it to 55°C can increase the savings by a further 3% to 6%. The actual kWh value of the savings varies, depending on the location of the SDHW system.

3.2 Improving geyser insulation

Another method to increase the performance of solar water heating is to increase the geyser's insulation, through the addition of a geyser blanket. In South Africa, the insulation of a geyser is given by the standing losses. In TRNSYS however, geyser insulation is defined by a factor known as the Tank Loss Coefficient (UA). Equation 1 gives the conversion.

$$\text{Standing losses} = \frac{UA}{3600} \times (T_s - T_a) \times 24 \qquad (1)$$

Where T_s is the geyser set point temperature, and T_a is the ambient temperature around the geyser.

For the purpose of the simulations, T_s was cho-

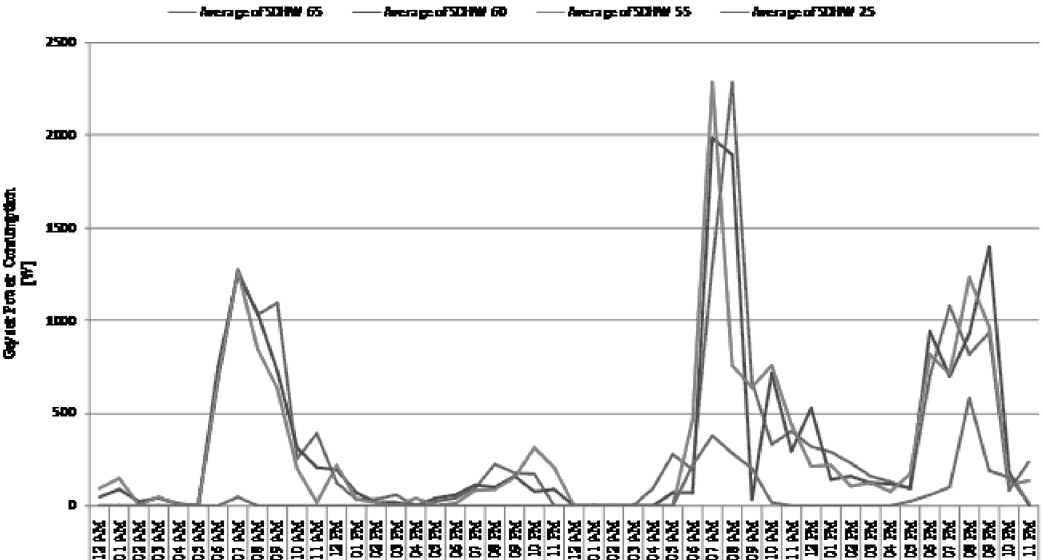

Figure 3: Comparison of average daily SDHW system geyser demand curves for various thermostat settings for January and July – Cape Town

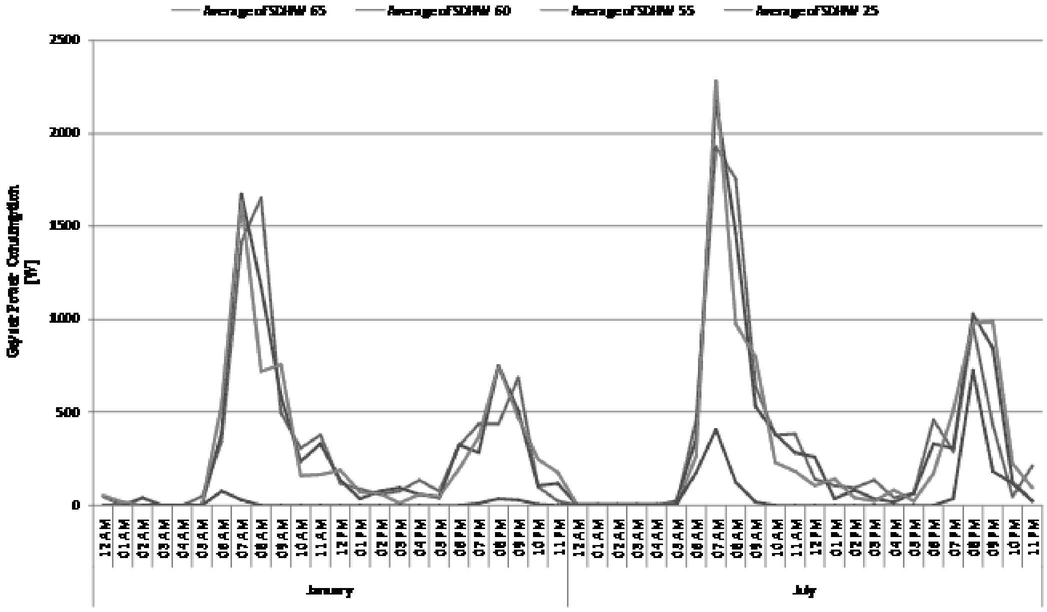

Figure 4: Comparison of average daily SDHW system geyser demand curves for various thermostat settings for January and July – Johannesburg

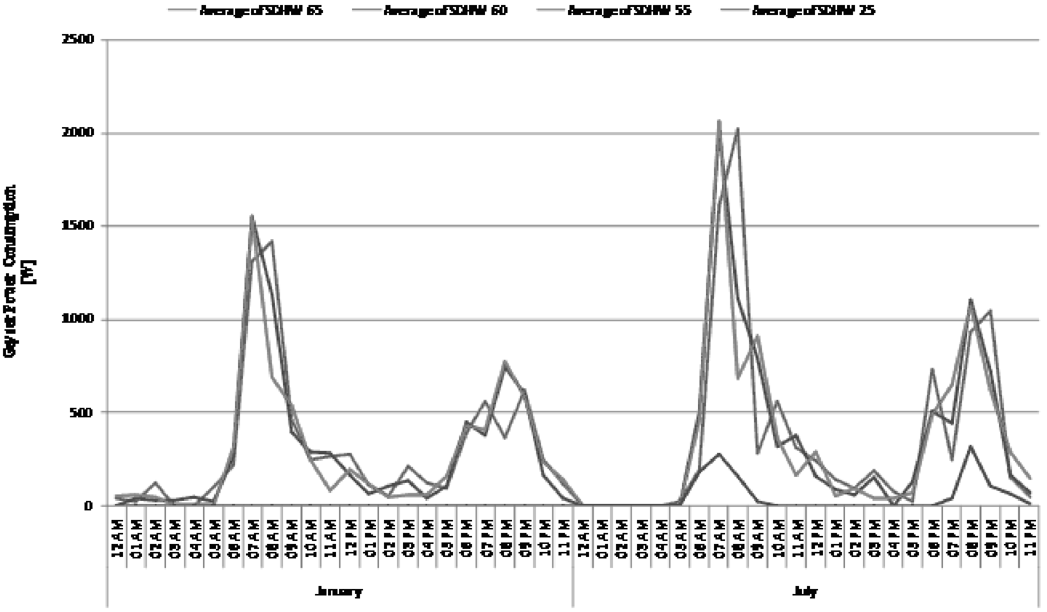

Figure 5: Comparison of average daily SDHW system geyser demand curves for various thermostat settings for January and July – Durban

Table 3: Energy consumption (and savings) due to reducing SDHW system geyser thermostat setting

		SDHW 65°C	*SDHW 60°C*	*SDHW 55°C*
Cape Town	January	177.32kWh	169.44kWh (4.4%)	159.06kWh (10.3%)
	July	330.01kWh	322.22kWh (2.4%)	316.96kWh (4.0%)
	Annual	2917.82kWh	2820.72kWh (3.3%)	2730.59kWh (6.4%)
Johannesburg	January	224.08kWh	215.84kWh (3.7%)	207.22kWh (7.5%)
	July	263.95kWh	259.05kWh (1.9%)	251.09kWh (4.9%)
	Annual	2839.74kWh	2747.83kWh (3.2%)	2655.75kWh (6.5%)
Durban	January	228.42kWh	218.84kWh (4.2%)	210.33kWh (7.9%)
	July	276.22kWh	269.65kWh (2.4%)	263.71kWh (4.5%)
	Annual	2926.61kWh	2833.25kWh (3.2%)	2742.72kWh (6.3%)

sen as 65°C and T_a was set to 19°C, as per manufacturer standing losses tests (Harris et al., 2007). The standing losses for the scenarios chosen are shown in Table 4.

Table 4: Geyser insulation ratings used for simulations

Tank loss coefficient (kJ/hr.K)	*Standing losses (kWh/day)*
4	1.23
5	1.53
6	1.84
8	2.45

The energy savings achieved for Cape Town, Johannesburg and Durban, can be seen in the energy consumption data illustrated in Figures 6 and 7.

In Figure 6, there is a marked increase in the geyser energy consumption in Cape Town between January and July. This can be attributed to the inclement weather experienced in the Cape during this time, which lowers the performance of a SDHW system significantly.

From the annual summary shown in Figure 7, it is quite apparent that an increase in geyser insulation can boost the energy savings yielded by a SDHW system. The savings for decreasing insula-

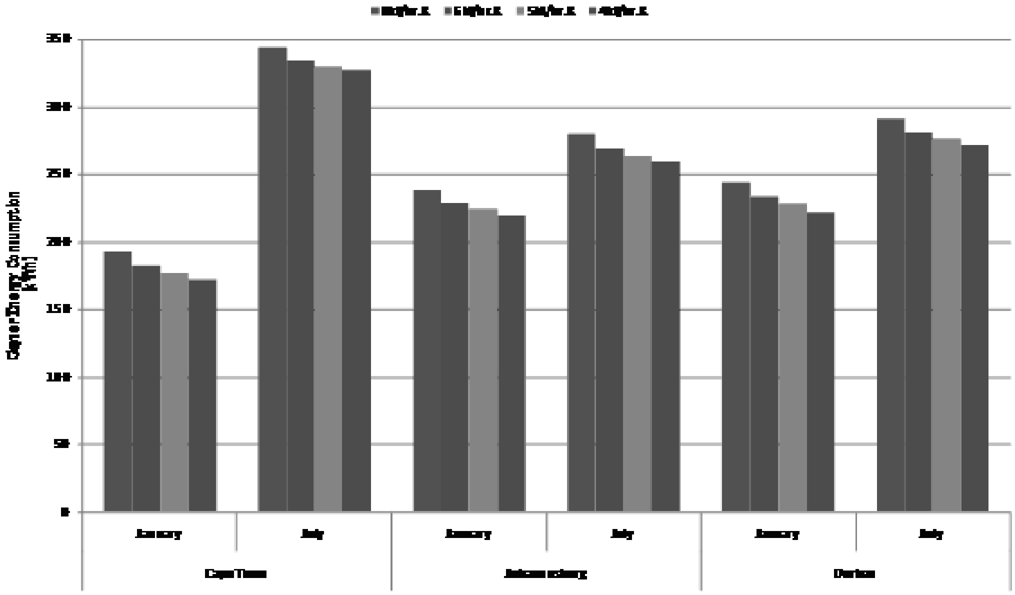

Figure 6: Comparison of monthly SDHW system energy consumption for different tank loss coefficients for January and July – Cape Town, Johannesburg and Durban

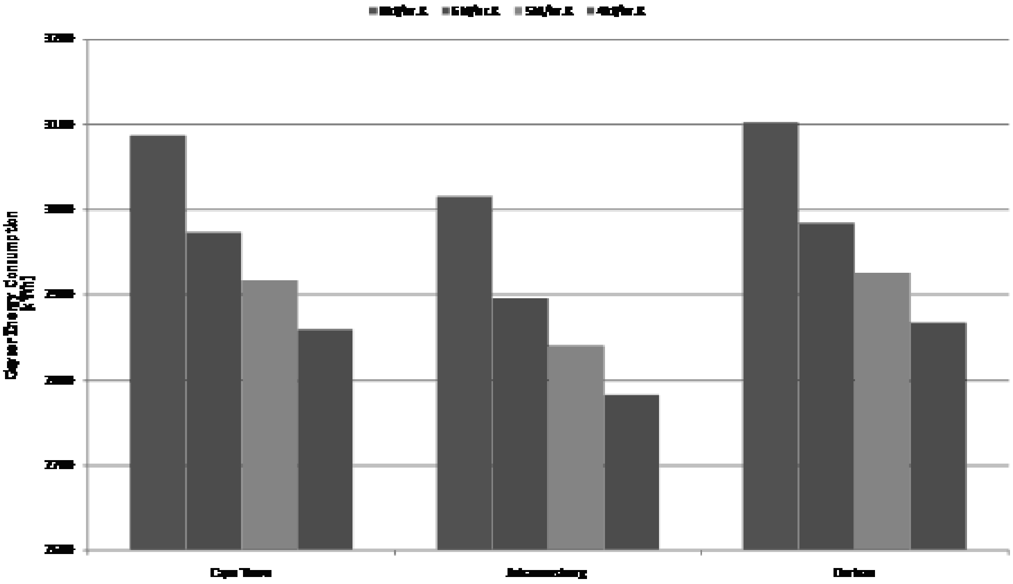

Figure 7: Comparison of annual SDHW system energy consumption for different tank loss coefficients for Cape Town, Johannesburg and Durban

Table 5: Energy savings due to increasing SDHW system geyser insulation from 8kJ/hr

	6kJ/hr.K	*5kJ/hr.K*	*4kJ/hr.K*
Cape Town			
January	5.37%	7.97%	10.71%
July	2.59%	3.97%	4.87%
Annual	3.68%	5.49%	7.35%
Johannesburg			
January	4.12%	6.15%	8.22%
July	3.95%	5.69%	7.29%
Annual	3.94%	5.83%	7.73%
Durban			
January	4.33%	6.40%	8.97%
July	3.51%	5.02%	6.60%
Annual	3.80%	5.67%	7.56%

tion levels, when compared against the SDHW system with a tank loss coefficient of 8kJ/hr.K, are summarised in Table 5.

From the results in Table 5, it would appear that doubling the geyser insulation so that standing losses decreased from 2.45kWh/day (8kJ/hr.K) to 1.23 kWh/day (4kJ/hr.K) increases the energy savings brought about by a SDHW system by approximately 7.5% annually, for all the 3 cities.

3.3 Changing the time of showering

Another method to enhance the performance of a solar water heating system is to alter the times during which hot water is used. Judging from the general shape of the demand curves produced when using the typical South African draw profile depicted in Figure 8, the water consumption profile appears to be fundamental to determining savings gained by the user of a solar water heating system.

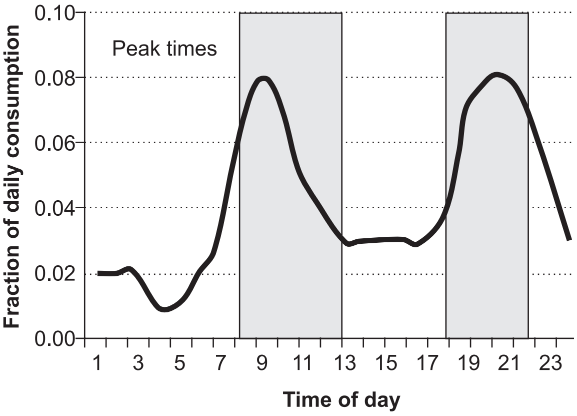

Figure 8: Typical South African water consumption profile
Source: Remund & Kunz (2003)

For example, if most hot water is used in the morning, a solar water heating system might have little to no effect, as compared to hot water usage that peaks in the evenings, especially during the summer months. This is due to the fact that most useful solar energy is only available in the afternoon.

In order to observe the impact of changing the time of hot water consumption, simulations were carried out for the hypothetical situation, where hot water usage takes place in one peak spread over 5 hours of the day, and is concentrated on a specific hour (x) with the distribution shown in Figure 9. The hours chosen for the simulations were 1am, 3 am, 5am, 7am, 9am, 11 am, 1 pm, 3 pm, 5 pm, 7 pm, 9 pm and 11 pm.

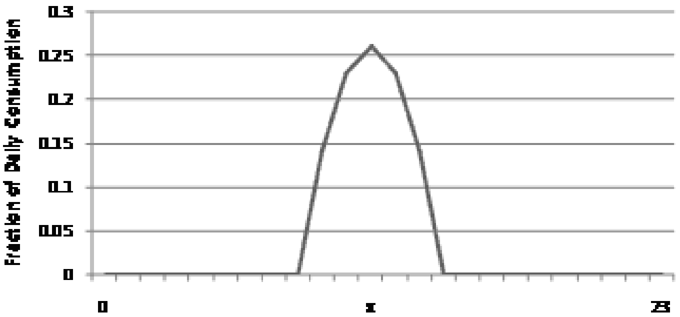

Figure 9: Hot water consumption profile used for simulations

For each hypothetical scenario, simulations were carried out for an EDHW system and a SDHW system with a 65°C thermostat setting. A comparison was then carried out for the monthly energy consumption for water heating for the two systems, in order to determine the hour of hot water usage that yielded the highest savings.

Figures 10 to 12 show the difference in energy consumption for an EDHW and an SDHW for each of the chosen hours, in the cities of Cape Town, Johannesburg and Durban. The first section represents the summer month of January and the second represents the winter month of July.

In Cape Town, the highest savings were achieved between 3 pm and 5 pm in the summer month of January, and between 1 pm and 3 pm in the winter month of July.

In Johannesburg, savings were at their highest in both January and July, when hot water usage peaked between 1 pm and 3pm.

Savings in Durban were maximised when peak hot water consumption occurred between 1 pmand 3 pm for winter and summer.

In general, maximum energy savings were achieved when peak hot water consumption took place early in the afternoon. It is thus concluded, that shifting most hot water usage to this part of the day, could help users of solar water heating systems realise maximum benefit from their investment. However, this may not be realistic, due to commitments such as work and school. Therefore, it is suggested that the user should aim to consume their

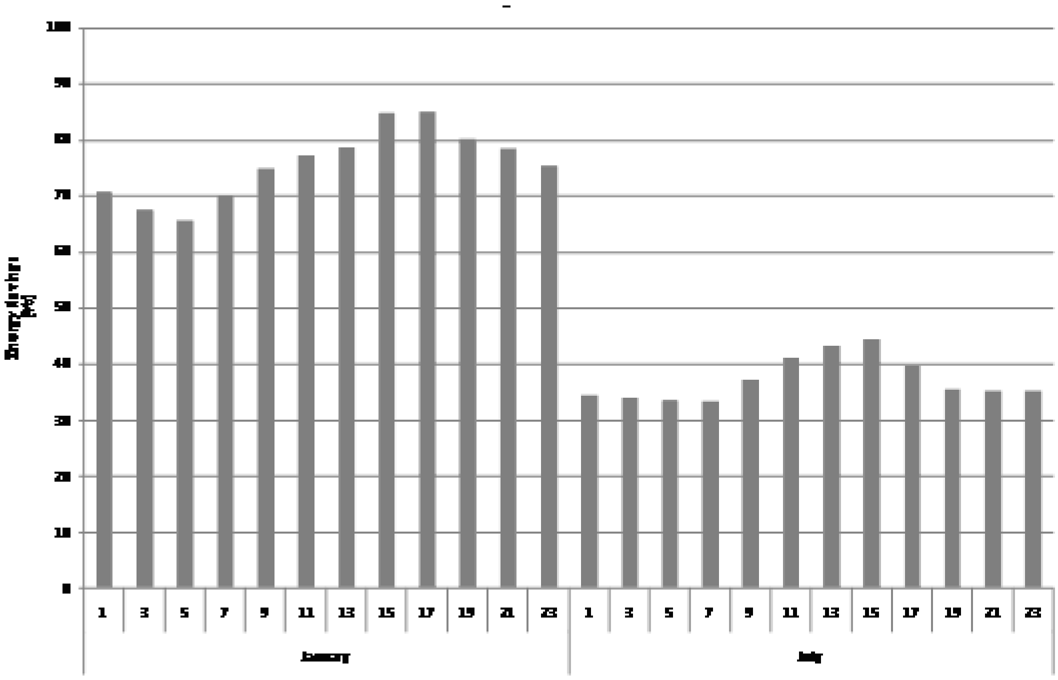

Figure 10: Energy savings yielded due to hot water consumption peaking at various hours in January and July – Cape Town

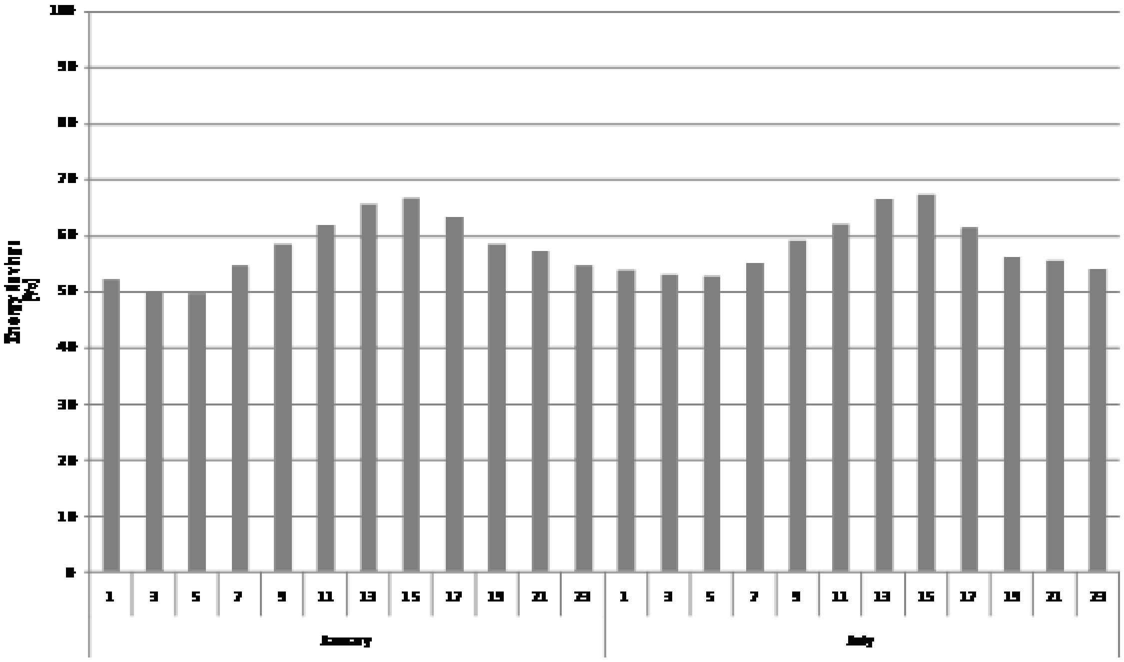

Figure 11: Energy savings yielded due to hot water consumption peaking at various hours in January and July – Johannesburg

hot water as close to these times as possible. The longer they wait after getting home, the more the savings are reduced.

Cape Town is a special case, due to the fact that its political time is derived from Durban – a whole 45 minutes ahead! As a result, the peak solar radiation actually occurs at roughly 1 pm, instead of 12 pm. This delay puts Cape Town consumers in a much better position to exploit SDHW systems.

3.4 Combined impact of suggested measures on energy savings

A simulation was done in order to examine the effects of implementing all 3 measures on a SDHW system. The simulation parameters that were changed are shown in Table 6.

Table 7 is a summary of the energy consumption of the improved SDHW systems and its savings, as compared to the original SDHW system.

Table 6: Simulation settings changed to implement energy saving measures on a SDHW system

	SDHW	*Improved SDHW*
Thermostat setting	65°C	55°C
Overall loss coefficient (standing losses)	5kJ/hr (1.53kWh/day)	4kJ/hr (1.23kWh/day)
Hot water consumption evening peak	8PM	7PM

For all three cases, the new demand curve maintains a similar shape to that of the original SDHW system. However, there is a difference in the energy consumption of the two systems, as can be seen in Table 7. The figures in brackets indicate the energy savings of the improved system, as compared to the original SDHW that was simulated.

From the results above, it can be concluded, that the implementation of all the energy saving measures discussed in this paper can improve the energy savings brought about by the use of a solar water heating system. Across the board, there was an annual increase in savings of 13% – 14%.

This is both an appreciable saving from a consumer perspective, and definitely something a utility would be interested in, given the contribution of water heating to their overall load.

3.5 Payback period analysis

A payback period analysis is a simple method to show the consumer how long it will take to recover the capital costs of the SDHW systems from the savings they make. This period is dependent on the initial cost of the system, as well as the cost of electricity (which will determine the monetary value of the savings).

The calculations are based on the cost and savings of a 2007, direct, flat plate, thermosyphon system. The annual consumption of electricity for water heating was treated as constant, and the electricity tariff was increased annually by 8%.

Usually, such a system would cost about R14 650 to install, but with Eskom's Solar Water Heating Initiative, the capital expenditure has been reduced to R12 385. The improved SDHW system will have the added cost of a geyser blanket, which is approximately R200. Table 8 shows the expected pay back periods (in years) for systems operating in Cape Town, Johannesburg and Durban.

Table 8: Estimated pay back period (in years) for SDHW Systems

	SDHW system	*Improved SDHW system*
Cape Town	10.20	8.96
Johannesburg	9.53	8.44
Durban	10.92	9.53

There are few important points to note about these payback periods. Firstly, they are based on electricity prices as at April 2008. With the 35% increase that Eskom requested soon to be implemented, tariffs are likely to rise. This will shorten the pay back period.

Another driver for the pay back period will be the initial cost of the system. The increasing cost of electricity is likely to drive up demand for SDHW systems. This trend could cause the initial cost of a SDHW system to decrease, further decreasing the pay back period.

Lastly, the pay back period was also calculated based on the assumption that the consumer will purchase an entire solar water heating system. If it is possible to retrofit the existing geyser with a solar thermal panel, the pay back period could be reduced even further.

From Table 7 it is evident that the implementation of the measures discussed in this paper can reduce the pay back period for a SDHW system.

4. Concluding remarks

It has been established that SDHW systems can reduce the amount of electrical energy used for water heating in a household. In this paper, it has been shown that implementing a few behavioural and operational changes could save even more energy. The changes discussed require little to no

Table 7: Energy consumption (and savings) due to implementing energy saving measures

		EDHW	SDHW	Improved SDHW
Cape Town	January	386.13kWh	177.32kWh	140.27kWh (20.9%)
	July	435.68kWh	330.01kWh	297.00kWh (10.00%)
	Annual	4855.10kWh	2917.82kWh	2494.22kWh (14.5%)
Johannesburg	January	387.47kWh	224.08kWh	190.03kWh (15.2%)
	July	436.92kWh	263.95kWh	231.75kWh (12.2%)
	Annual	4859.13kWh	2839.74kWh	2433.65kWh (14.3%)
Durban	January	372.98kWh	228.42kWh	192.93kWh (15.5%)
	July	409.21kWh	276.22kWh	244.49kWh (11.5%)
	Annual	4587.87kWh	2926.61kWh	2541.64kWh (13.2%)

capital investment on the part of the utility, and are beneficial to both the utility and the consumer.

From a consumer perspective, putting these measures into practice requires little effort on their part. Turning down a thermostat and installing a geyser blanket are both quick, once-off procedures. Changing the hot water consumption pattern might be a bit more difficult, due to several external social factors, which drive hot water usage. However, the promise of such significant energy savings would probably prove incentive enough for them to try.

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