SMART HOMES: ENERGY EFFICIENCY BASED ON DEMAND SIDE MANAGEMENT AND GAME THEORETIC ALGORITHM

ABSTRACT
The smart home is an integral part of future energy management and control. The reduction of domestic energy consumption and improved energy efficiency of households will require intelligent systems that constantly monitor the household electricity usage and provides real-time updates to the user. This will lead to a bill reduction for households and energy efficiency. In this paper we investigate two concepts, namely; (i) the effect of a demand side management system, where a smart meter prototype was provided to each household depicting detailed and real-time information to the user, and (ii) a Game theoretic algorithm to manage and minimize the daily electricity expenditure and improve the energy efficiency of the domestic household.

Computational results and data are provided and discussed that determine which system would work the best.

KEY WORDS
Smart homes, energy management, demand side management (DSM) and game theoretic algorithm.

1. Introduction

Prior to 1990, less than one-third of South African households had access to electricity [3]. To ensure more equitable access to electricity, that demand for electrical energy has increased and it is expected this will continue to increase significantly in the next five to ten years. Since 1996, according to results of census data from Stats SA, the largest increases in households using electricity occurred for cooking (14% increase) and lighting (12% increase) relative to space heating (2% increase) [16]. Available data indicates that 89% of South African households use electricity for lighting, 77% of households (across all income groups) use electricity for cooking, 66% of households use an electrical appliance such as the electric geyser (31%), electric kettle (23%) or an electric kettle and stove (7%), to heat water and 41% of households use electricity as the main source of energy for space heating and close to two fifths of (39%) of homes use no energy source for space heating. The latest residential energy survey by the Department of Energy South Africa show that on average, South African households spend 14% of their total monthly household income on energy needs which is higher than the international benchmark of 10% for energy poverty [18].
To achieve operational stability and reliability the electric utility needs to maintain a balance between its generation capacity and the increasing consumption demand by the end-consumers. This increase in demand will require an expansion to the generation capacity infrastructure. To reduce capital expenditure, the main energy supplier is actively encouraging consumers to reduce electricity consumption. Many people are under the impression that domestic households/residences use the least amount of electricity in South Africa, but are expected to make the most sacrifices in times of shortage. More than a third (34%) of households felt that they pay “far too much” for what they receive, with another 38% saying they pay “too much”. Just under a quarter (22%) felt they pay “about the right amount” for what they receive. Very few (3%) said they “pay too little” and 3% were uncertain [18]. At this time the stability of the electricity grid is in the hands of residential users. ESKOM the utility company in South Africa has launched many initiatives to try and maintain stability. One such initiative is the National Power Alert Banner on television. This Banner informs viewers of the state of the electricity supply for the country during evening peak hours, and calls upon the public to respond by switching off all less urgent appliances when the situation becomes critical [3]. Other solutions include, introducing more green energy, renewable energy and energy harvesting techniques to the electrical grid system. Increasing air pollution from coal-based electricity generation increases the carbon footprint. South Africa is ranked among the top twenty largest carbon emitters per capita because approximately 67% of its primary energy supply is derived from coal [17]. Therefore increasing demand for electricity and clean energy means that the current electricity supply must be more efficiently utilised.
Demand side management and Game Theoretic models are two techniques proposed in this paper to assist the consumer to intelligently reduce electricity consumption. In this paper, we analyse each model to determine which model provides the optimum results to manage and minimize the daily electricity expenditure and improve the energy efficiency for future smart homes.

2. Background and definitions

Governments and power utilities are investing large sums of money towards research and development of energy saving projects. The expected outcome of all of these projects is to achieve reliable and improved power quality. One of the objectives is to introduce more renewable energy sources for consumption. Another objective is to incentivise consumers to exercise more control over their electrical energy consumption based on utility penalties and sharing of real time information.

The following definitions will be used in this paper and are often used in discussions on smart or intelligent electricity usage:

1.1 Demand side management: mechanisms to optimise consumer demand for electrical energy by encouraging the consumer to use less energy via various punishment and reward schemes [4].

1.2 Smart homes: A building adequately equipped with distinctive structured wiring and circuitry to authorize occupants to remotely act or route an assortment of automated home electronic devices [5].

1.3 Game theory: The investigation of method's in which interacting decisions of economic agents yield end results with respect to the preferences of those agents, where the decisions in question might have been predetermined by none of the agents [6].

Today's energy efficiency industry can trace its ancestry to the heady, turbulent 1970's. The term demand side management was coined following the 1973 and 1979 energy crisis. It was introduced publicly by electric power research institutes in the 1980s [4].

In South Africa, the media has published several articles about the electricity crisis, billing problems and energy efficiency. A study in 2014 by Electricity resellers association of SA (ERASA) showed that the roll out of smart meters in some cities in South Africa do not meet standards (SANS 473:2013 and NRS 071:2013), and it warned that inconsistencies could cause major future billing problems. The primary reason here was the installed meter's was not user friendly and could not share correct and real time data with the municipalities nor the consumers [7][8].

The mathematical theory of games was invented by John von Neumann and Oskar Morgenstern in 1944. Today Game theory is used in many applications, such as: Resource allocation, Networking, Biology, artificial intelligence (AI), Economics and Politics [6]. Here we incorporated AI and Game theory to control the electricity usage of a Smart home, where the utility would adopt a penalty system for non complying users in the game.

3. Methodology/System Models

In this section, the theory and the design of the two concepts that were investigated are discussed, namely: Demand side management and a Game theoretic algorithm to manage and minimize the daily electricity expenditure and improve the energy efficiency of the domestic household.

3.1 Demand side management

As the demand for electricity increased, public campaigns to promote energy awareness increased. In a bid to decrease electricity usage, Eskom the utility company in South Africa embarked on campaigns to educate society about the importance of saving energy whenever possible. The latest drive for energy-saving tips, dubbed the "49 Million Campaign,". It calls upon all 49 million South Africans to embrace energy-saving as a culture and to join the global movement towards ensuring a sustainable future. Targeting the demand side of the dilemma as a short-term response, whilst supply side improvements are simultaneously pursued on a more long-term basis [18].

In order for the consumer to start saving electricity at home, he/she would firstly need access to the relevant data. A smart meter prototype was designed and constructed. Domestic users will have this smart meter installed which provides real time information on energy consumption such as: cost, time duration, future estimated costs and CO2 emissions. A PIC 16F88 microcontroller was used for computation and analysis of the data. The firmware was written in the C language using Code Optimizing C Compilers (CCS C Compiler) and Microchip MPLAB IDE. Figure 1 shows the "menu" and the information displayed on the LCD to the user in sequence by the use of a push button.

Looking at the menu in detail, Power drawn for a particular period shows the maximum and minimum values in (watts) for the appliance being used. The recording time shows for how long the appliance has been used for. The Energy consumed based on the calculations blow, the user is able to view their (kWh) or units being consumed. The next menu calculates and displays the predicted cost to the user for the particular appliance being used. The last menu allows the user to view the carbon emissions for the appliance being measured.

Figure 1: The menu.

For the measurement and mathematical calculation section of the electricity the use of a current sensor in the form of an IC ADE7756an series was used. The IC has two op-amps to measure the current, which is sampled and sent to the PIC microcontroller via (analogue to digital) A/D converters. Values are based on the following standard calculations as follows:

$$P\ (watts) = V\ (volts) \times I\ (amps)$$
$$P\ (watts)/1000 = kW$$
$$kW \times hours\ of\ operation = kWh$$
$$kWh \times kWh\ rate = cost$$

[10]

Cost per kWh=R0, 94.

$$kWh \times 0.99kg\ CO2\ per\ kWh = c02\ emissions$$

The emission rate for South Africa is 0.99kg. [11]

An Arduino UNO board along with relays were used for controlling (i.e. switching on/off) appliances.

The meter would simply be plugged into the wall socket and all appliances connected to its outputs. This system gave the user the ability to switch appliances on/off manually using their own discretion based on the cost they see on the LCD or the system could self-manage the switching of appliances at specific times. Figure 2 below depicts the smart meter prototype that was used for the demand side management investigation.

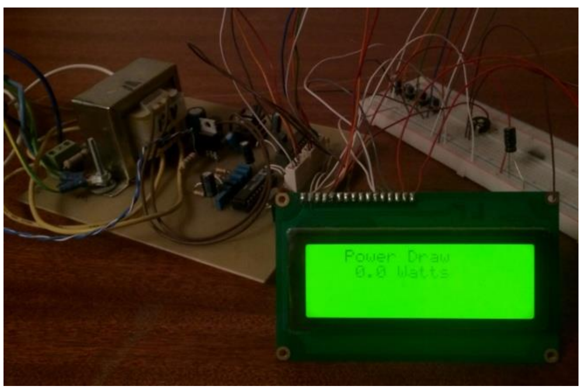

Figure 2: The smart meter prototype.

The South African Audience Research Foundation (SAARF) Living Standards Measure (LSM) is the most widely used marketing research tool in Southern Africa. It divides the population into 10 LSM groups, 10 (highest) to 1 (lowest). The SAARF LSM is a unique means of segmenting the South African market and groups people according to their living standards using criteria such as degree of urbanisation and ownership of “major appliances” [12]. Using the SAARF LSM model, we sub-divided homes into three categories LSM1-4, LSM5-7 and LSM 8-10. For this paper, we specifically analysed the results for the LSM1-4 group. This group is most vulnerable to the increasing cost of electricity and constitute a large percentage of household users. Research on energy usage patterns of low income households indicate that on average poor South African household spends 14% of total monthly household income on energy needs [16]. The following appliances were identified as frequently used by consumers from LSM group 1-4, namely: Radio, Stove hot plate, Television (25-inch colour), Light Bulbs (CFL), Heater (Portable), Iron, Charger for cell phones. Consumer usage patterns, cost to the user and determination of the effectiveness of smart meters in reducing energy consumption and expenditure within this group are analysed.

3.2 Game Theoretic Model

In 2010 the SA government introduced the inclining block tariff (IBT) which allows electric utilities to charge consumers on a sliding scale for electricity usage. The purpose of IBT was to penalise high income earners who wasted electricity whilst reducing the impact of rising electricity prices on low income earners [16].

In order to gauge how South Africans handled previous electricity price increase, they were asked to indicate which of the following strategies they employed to deal with the increase. The options were:

- Continue to use the same level of electricity and pay the extra amount for it.
- Reduce the amount of electricity used.
- Use other energy sources.
- Other strategies.

The strategy employed by most South Africans in the past year to cope with the rising electricity costs was to reduce the amount of electricity used. These results clearly show that future energy price increases will have a bearing on the types of energies used and would encourage more energy saving and energy switching. Further analysis revealed that it was mostly households with a medium and high living standard that stated they would reduce the amount of energy used [18].

A game theoretic model for optimising the electricity consumption of a household, with the final goals of both minimizing the daily energy expenditure and improving the efficiency of the whole electricity grid was designed. Users agree to save with respect to their energy demands.

The basic algorithm structure defines the utility as one player and the household (n) user as another player. Game theoretic algorithm was used where each household user plays directly with the utility. There is no communication between household users. The code was written and simulated using MATLAB.

Three strategies were used in the code, namely: ALLS (All Save), ALLNS (All Do Not Save), RANDOM (Save When Given an Incentive).

The population or amount of households in this simulation is 100 households (or a percentage of 100%) during a period of 6-12 months. The aim is to incentivise ALLNS and RANDOM users to reduce energy consumption as often as ALLS. This is achieved by generating a penalty whereby if a user does not save, the user has points deducted or in a real life situation a tariff increase is imposed.

The payoff matrix described below:

		Utility	
		save	*no save*
User	*save*	R	S
	no save	T	P

Where R>T>S>P

		Utility	
		save	*no save*
User	*save*	6,6	-3,3
	no save	3,-3	-5,-5

Table 1 below, explains how the system should work in order to achieve a constant saving pattern for three users over a period of time.
Where:

$$U = \text{Utility}$$
$$C = \text{a group of households}$$
$$c = \text{a single home}$$
$$c\ \forall [C] \text{ for each iteration}$$

Here we look at {3c, U}

Strategy	*UTILITY*	*USER1*	*USER2*	*USER3*
ALLNS	Save	No Save	No Save	No Save
RANDOM	Save	Save	No Save	No Save
ALLS	Save	Save	Save	Save

Table1: The proposed saving pattern

Prior to applying the Game theoretic model, Figure 3 shows typical usage patterns for the three strategies namely; ALLS, ALLNS, RANDOM. We notice that more households tend to waste electricity; the graph illustrates the amount of households that are saving and those that aren't for the three strategies. Only 20% of households are actively saving electricity, 25% are occasionally saving electricity and 55% and not saving electricity.

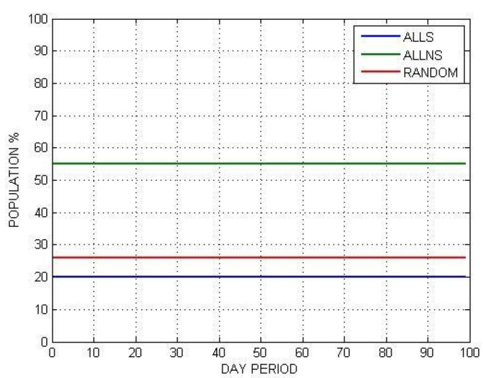

Figure 3: The usage patterns prior to the Game Theoretic model

4. Results

In this section, we present simulation results and assess the performance and differences of our proposed systems. We conclude by selecting the appropriate system to manage and minimize the daily electricity expenditure and improve the energy efficiency of the domestic household.

4.1 Demand side management

As mentioned previously, the results for the LSM1-4 group are analysed. The appliances used by this sector are: Radio, Stove hot plate, Television (25-inch colour), Light Bulbs (CFL), Heater (Portable), Iron, Charger for cell phones.
Electricity usage using the smart meter prototype was measured over a one-month period. Table 2 shows the data that was recorded for each appliance.

Appliance (LSM 1-4)	Average wattage	Average hours used per month	Approx. kWh used per month	Cost/month @94cents per kWh
Radio	70	100	7	6.58
Stove hot plate	400	3	1	1.128
Television (25 inch colour)	200	180	36	33.84
Light Bulbs (CFL)	26	300	8	7.332
Heater (Portable)	1500	180	270	253.8
Iron	1100	12	13	12.408
Charger for cell phones etc.	75	13	1	0.9165
TOTALS			336	316.0045

Table 2: Recorded data for one month LSM 1-4

Using the data from Table 2 the cost per appliance to the consumer at the set tariff of 94c/kWh versus average hours per month is plotted and shown in Figure 4. By doing this we could differentiate usage patterns per appliance over a one month duration.
The heater consumes more power compared to the other appliances, resulting in higher expenditure when this device is used. This could lead to higher tariffs rates during peak periods. This type of usage will change in the summer months where the heater will be used less or not at all and other appliances would consume more.

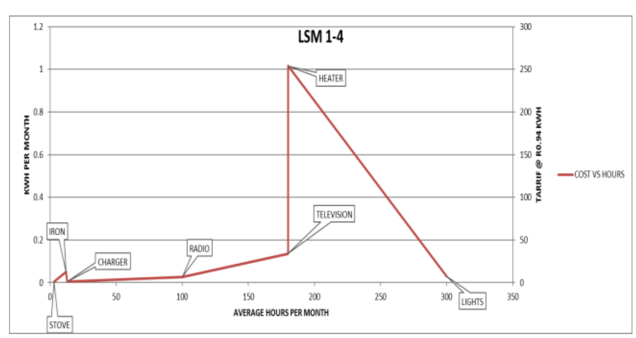

Figure 4: Usage patterns

The total cost to the user based on the usage patterns in Table 2 and Figure 4 is plotted and shown in Figure 5. It is seen here that for this usage pattern for one month the household user's expenditure for LSM 1-4 is R316.00.

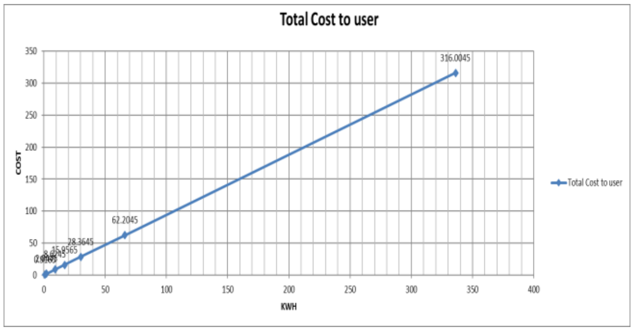

Figure 5: Total expenditure to user.

Since LSM 1-4 is the lower class, the monthly cost in Figure 5 might be too high. An alternate method was used to try and curb the wastage by introducing an automated system where on/off intervals for appliances based on household usage patterns were used. By using this system, non-essential appliance usage time can be decreased, which could create room for extra usage times on important appliances. In turn this can lead to lower monthly expenditure. Usage times for the Television, Radio and Iron were reduced by half since these were non- essential appliances this is seen in Figure 6.

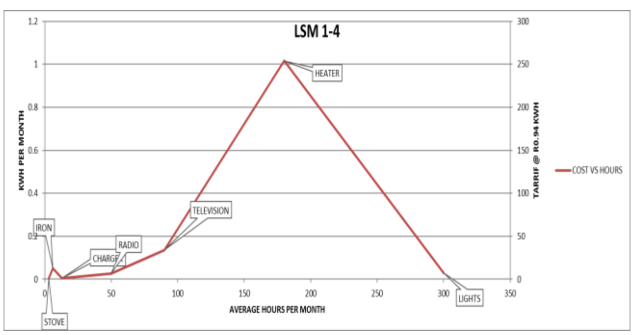

Figure 6: Automated usage patterns

Figure 7 shows a reduced expenditure of R289.59 when just three non-essential appliance usage times are reduced by half, that is a saving of R26.41.

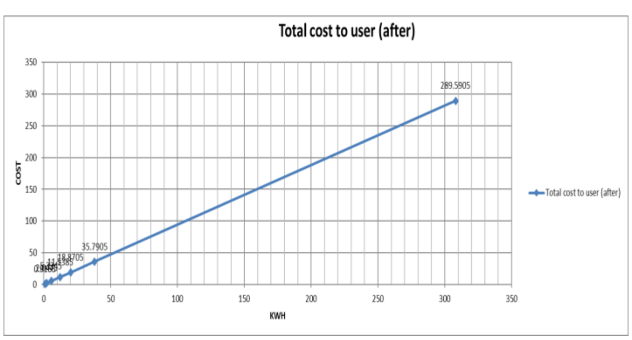

Figure 7: Total expenditure to user after automation.

This system has a specific disadvantage though, some users did not agree with the time intervals specified for their specific appliance usage.
Therefore, it was concluded that in order for a more robust model to be achieved, sufficient data is needed over a lengthy period of time. After much correspondence with the utility company and other consulting firms in South Africa it is safe to say that currently there is insufficient load profiles data from individual appliances, but only of whole-home loads. The data source we seek is probably one of the most important in the SA domestic sector now, and is not yet serviced (i.e. there is no structured programme in place to resolve this need).
Individual appliance profile data is the only way to determine impacts of:

- Appliance energy efficiency programmes (i.e. energy star rating).
- Appliance-focussed DSM projects or demand response management systems.
- Renewables programmes on household loads.

When individual appliance usage data becomes available it will be possible to optimise the time and duration allocated for each appliance based on this data.

4.2 Game Theoretic Model

In this game model we have the utility as one player and the household (n) user as another player. The strategies were three kinds. The population or amount of households in this simulation is 100 households (or a percentage of 100%) for each strategy at a period of 6-12 months. The aim is to increase the number of households saving in this period; this is done by generating the penalty if the household does not save. Selfish behaviour by players or in this case no saving of electricity may lead to a suboptimal equilibrium, where players through their actions, reach an undesirable steady state (in addition to often not being Pareto optimal) [13]. Hence, penalty schemes are proposed to steer players towards constructive behaviour. A penalty is imposed so that if a household does not save the household has points deducted or in a real life situation a tariff increase is imposed. We investigated the impact of this Game theoretic model on increasing electricity savings and the result of the simulation is shown below.

Based on the game and the system model above, the code and simulation was done using Matlab. The code was run multiple times for a number of iterations based on the 6-12-month period stipulated. It can be concluded that the game theoretic model encourages more users to start saving.

Comparing Figure 8 and Figure 9 to Figure 3, it can be observed that the household saving strategy tends to increase while the other strategies decrease. As the time period over which the model runs is increased, the other strategies tend more and more to reduce while the users saving increase. In this case based on the amount of households it took approximately 1 month for the cross over. We also notice an equilibrium based on the results of this Game theoretic model where ALLS users are now 55%, ALLNS users are 25% and RANDOM users are 20%.

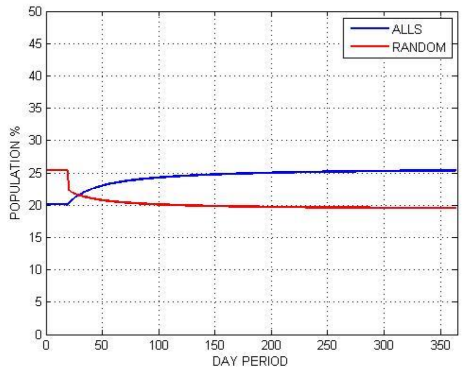

Figure 8: The usage patterns after the Game Theoretic model ALLS vs RANDOM.

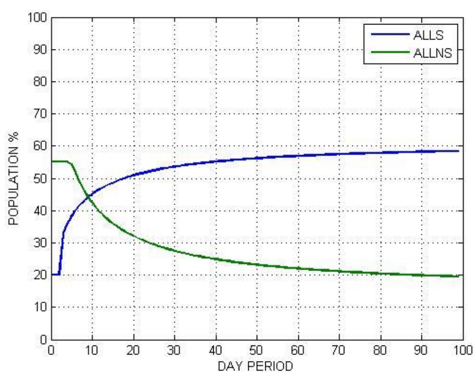

Figure 9: The usage patterns after the Game Theoretic model ALLS vs ALLNS.

Further investigation was done in order to shorten the cross over period. Results indicate that as the population size decreases, the system tends to work at a faster rate i.e. the cross over point occurs sooner. Thus it can be concluded that the population size will determine the time taken to achieve an equilibrium in the system. Figure 10 shows that when the population size is decreased to half the original size it takes approximately 1-2 weeks for households to cross over.

A trend line and formula for the ALLS graph was obtained using Microsoft Excel. The trend line provides an approximation in which direction the saving patterns are going. Based on the formula shown in equation (1), it may be possible to achieve a cross over at 7 days.

$$y = 5.2385\ln(x) + 15.831 \qquad (1)$$

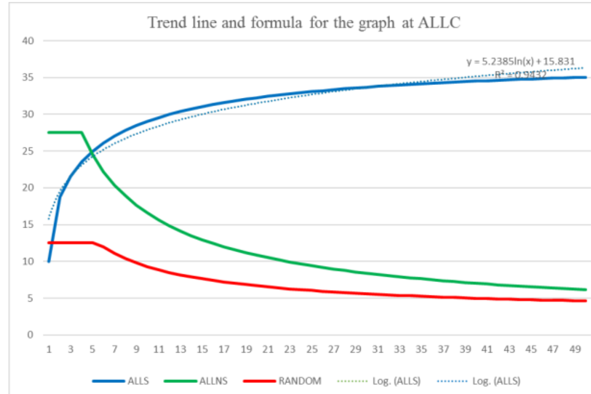

Figure 10: The speed of the Game Theoretic model at half the population size with trend line.

4. Conclusion

The paper proposed two models to manage and minimize daily electricity expenditure and improve the energy efficiency of the domestic household. These system benefits will positively impact the utility by reducing demand on the electric energy infrastructure and lead to direct and indirect economic savings. Numerical results show a significant benefit for both systems.

For the Demand side management system which uses a smart energy meter, it can be concluded that in order for a more robust model to be achieved, sufficient data is needed over a lengthy period of time for specific appliance profiles. A possible disadvantage of this system is that some users may not agree with the time usage intervals specified for their specific appliances.

The Game theoretic model, simulation results show a positive impact on the actual goal of this paper (i.e. to manage and minimize the daily electricity expenditure and improve the energy efficiency of the domestic household). It can be concluded that home owners with different strategies towards electricity saving can be induced to increase their electricity saving strategy according to this model. The larger the population the longer the time required to achieve a balance of positive results.

The proposed work in this paper represents an initial step towards a research area that requires further attention for future Smart homes. Alternatively, for future research we need to develop more advanced versions of the proposed work that would also correctly react to real time events.

Clearly it is up to all South Africans to make sure they are legal and responsible users of this precious resource – Electricity.

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