CHAPTER 1

ENERGY MANAGEMENT IN SOUTH AFRICA

In 1989 Eskom responded to the South African rural communities' electricity needs by embarking on a countrywide electrification drive. This drive has the potential to generate over 5 million new residential customers by the year 2005. Various studies have proven that the load-profile of residential consumers tends to be peaky in nature, pronouncing in the morning between 06:00 and 09:00 and again in the evening between 18:00 and 20:00. The result of this electrification program will therefore cause a major impact on the Eskom national grid for it will definitely increase the system peak [1].

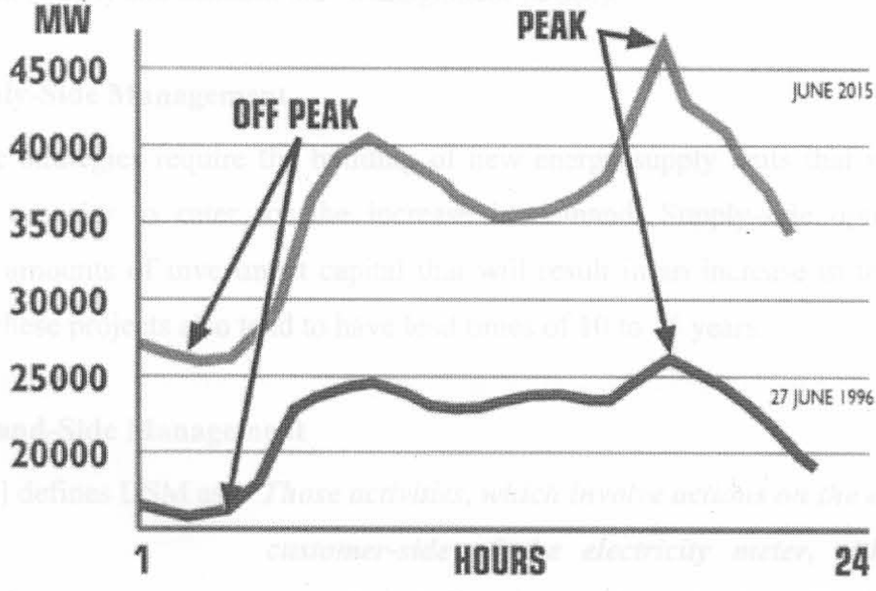

Figure 1.1: National demand profile - Actual values of 1996 compared with estimated simulation profiles for 2015 [1].

Figure 1.1 illustrates that in 1996 analysts expected the South African peak demand to double over a period of 20 years. These calculations were based on a predicted deterioration in peak to off-peak demand ratio of 17%, starting in 1996. The deterioration in load factor means that the supply capacity will not be used effectively all the time, and given a projected load growth of approximately 3% p.a., supply infrastructure will be required to increase over time, including the building of new power stations [1].

The construction of additional new supply infrastructure is very expensive and will result in a significant electricity price increase. Various other options were considered to utilise the existing network in a more efficient method. These options are defined as load management-options and will be briefly discussed in the following sections.

1.1 LOAD MANAGEMENT

All around the world utilities must be pro-active in their supply strategies by predicting the future requirements of their existing consumers as well as new clients added to the network. A number of strategies can be implemented to match the supply with this increase in demand. These strategies can mainly be categorised into two approaches i.e. supply-side management (SSM) and demand-side management (DSM).

1.1.1 Supply-Side Management

Supply-side strategies require the building of new energy supply units that will improve generating capacity to cater for the increase in demand. Supply-side options require substantial amounts of investment capital that will result in an increase in the electricity tariffs and these projects also tend to have lead times of 10 to 15 years.

1.1.2 Demand-Side Management

Gellings [2] defines DSM as: ***"Those activities, which involve actions on the demand – or customer-side of the electricity meter, either directly caused, or indirectly stimulated by the utility."***

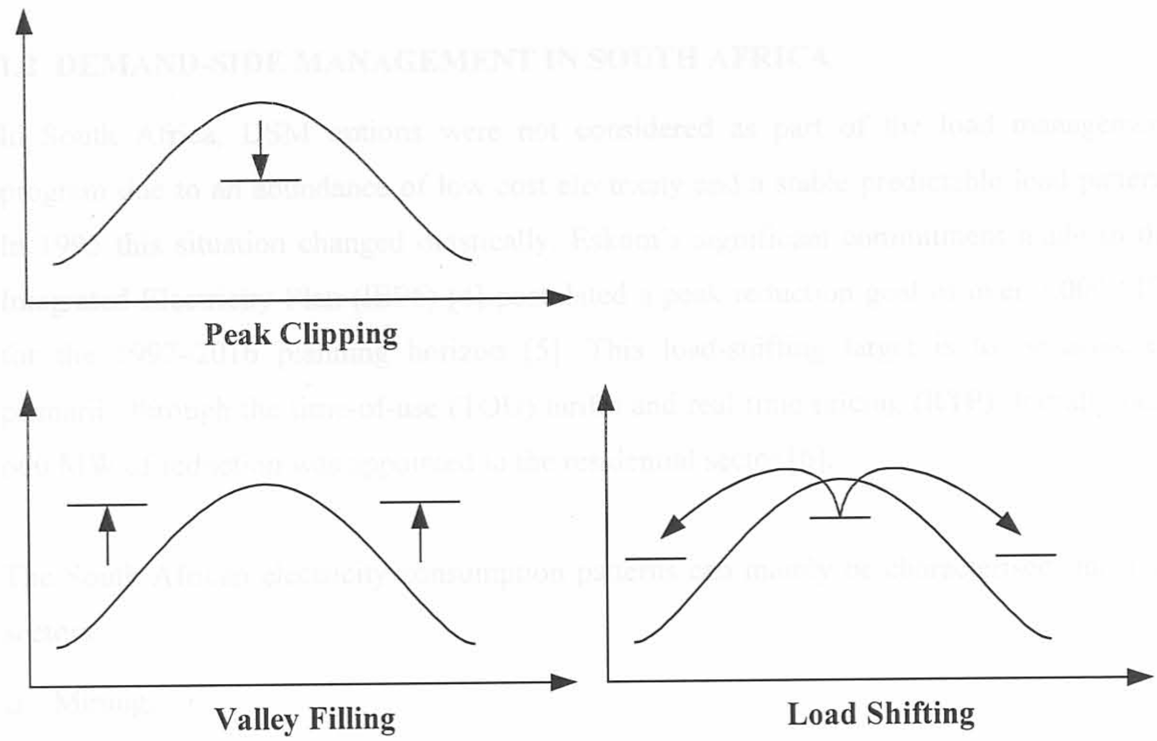

Figure 1.2: Various load-shaping objectives [2].

DSM activities, as illustrated in figure 1.2, are deliberately designed to alter the load shape by modifying the timing and electrical energy consumption, effectively shifting or lowering the load during peak demand periods [3]. The result will make for a higher load factor with demand being spread more evenly during the day thereby contributing to a lower peak and better utilisation of generating capacity.

DSM activities range from simple methods of influencing the behaviour of customers via information and educational programs [4] to the installation of expert load-control systems. Most of these solutions are extremely cost effective and can be implemented within a maximum period of 5 years. For this reason the subsequent sections will be dedicated to current and future DSM development areas in South Africa.

1.2 DEMAND-SIDE MANAGEMENT IN SOUTH AFRICA

In South Africa, DSM options were not considered as part of the load management program due to an abundance of low cost electricity and a stable predictable load pattern. In 1995 this situation changed drastically. Eskom's significant commitment made in the Integrated Electricity Plan (IEP6) [4] postulated a peak reduction goal of over 7,000 MW for the 1997–2016 planning horizon [5]. This load-shifting target is to be achieved primarily through the time-of-use (TOU) tariffs and real-time pricing (RTP). Initially only 600 MW of reduction was appointed to the residential sector [6].

The South African electricity consumption patterns can mainly be characterised into four sectors:

- Mining,
- Industrial,
- Commercial and
- Residential.

Generally the residential sector has always made up a smaller portion of the demand than the Mining-, Industrial- and Commercial sectors. For the first time, on 25 June 1992 and 8 July 1992, the Eskom system peak demand record occurred in the evening. This trend has continued thereafter and is attributed to the impact of the electrification of large numbers of new residential customers [7]. At that stage little research and implementation, compared to the mining- and industrial sectors, has been done in the field of residential demand-side management (RDSM).

With a more pronounced residential client and IEP6 reduction levels caused analysts to focus more on RDSM as a viable solution.

1.3 RESIDENTIAL DEMAND-SIDE MANAGEMENT

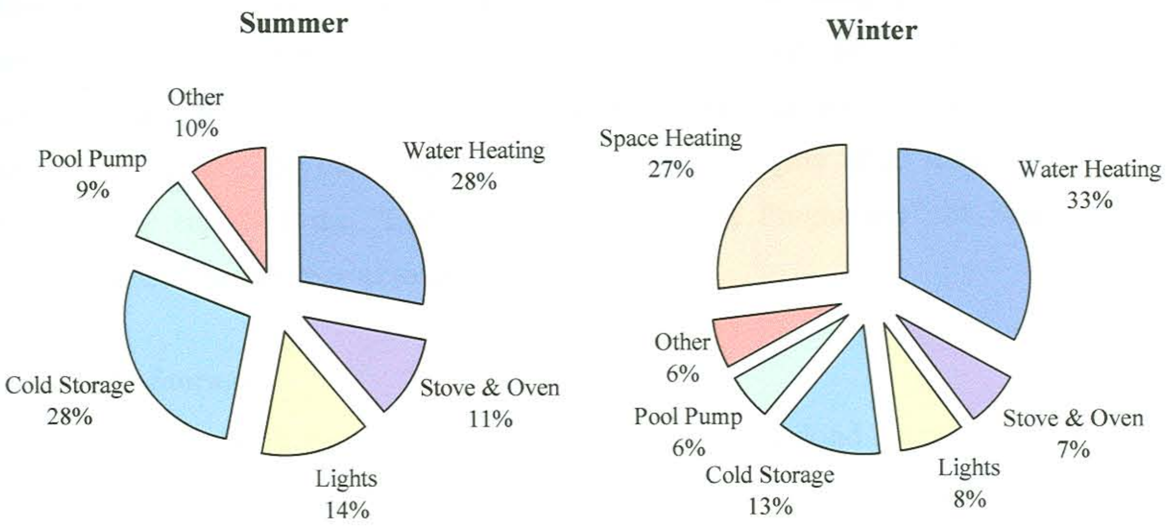

Figure 1.3: The South African residential load distribution [8].

If one takes a closer look at figure 1.3, it is clear that only a handful of appliances comprise more than 80% of the residential energy consumption. Various RDSM initiatives rose to the occasion in order to minimise the effect of these major energy-consuming devices, which include [9]:

- Payment, as well as metering and tariff structures,
- Residential dwelling thermal isolation projects,
- Energy efficient lighting,
- Reducing breaker ratings,
- Alternative energy sources,
- Energy efficient appliances,
- Energy efficiency awareness,
- Cold storage appliance efficiency standards [10] and
- Hot water load-control (HWLC) [5].

1.3.1 Lights

Electric lighting is very convenient and easy to use, allowing people to get easily accustomed to it. Unfortunately this also leaves an opportunity for energy wastage due to ignorance and human error. Lights are a burden on the maximum demand (between 9% and 13%) because of the simultaneous switching of lights after sunset [8]. Eskom successfully launched the "Energy Efficient Lighting Programme" in South Africa, promoting CFL-technology as savings initiative.

1.3.2 Cold Storage

Cold storage is one of the by-products of electricity that mankind is unwilling to separate himself from. It is a necessity and the residential consumer would rather pay for the use, no matter the cost, than be faced to live without it.

Van Tonder [11] discovered that cold storage appears to be an excellent candidate as an interruptible load. Intelligent control systems are required to control the refrigerators and it must be integrated in to the refrigeration circuit. The refrigerator or deep fridge can then be interrupted for longer times when not opened frequently, and the inside temperature can be controlled at a higher allowable set point during high-demand periods.

The major disadvantage is the installation of these control circuits into existing refrigerating units. Cold storage control must rather be seen as a long-term solution by s3elling the cold load-control technology to the manufacturers, integrating the control circuit into the cold storage unit during manufacturing. The utility on the other hand can also subsidise a percentage of capital costs to the residential user for purchasing one of these refrigerating units.

For the time being it is not cost-effective to control cold storage units but Thorne's [10] research confirmed that it is definitely economically feasible to optimise the units in terms of isolation and energy conversion.

1.3.3 Space Heating

In South Africa, space heating is only prevalent during the winter as the climate is usually much warmer during summer times [8]. The energy consumed depends largely on two factors:

- The ambient temperature and
- The type of heating unit.

In a pilot study conducted by Hydro-Quebec [12], electric space heating systems appear to be poor candidates for direct-load-control. The authors conducted that indirect load-control will be a better option for load management purposes.

1.3.4 Water Heating

It is likely that a home's single largest electricity expense is water heating and typically accounts in the region 25% to 35% of the domestic consumer's electricity bill [8]. The effect of water heating on the maximum demand is the largest in the mornings, with a steep gradient, and more constant during the evenings. This is due to the fact that the average person gets up at around six and has to be off to work at seven whereas in the evening there is more than enough time to prepare for bed.

The predominant advantage of HWLC is that it only shifts energy by means of peak clipping and valley filling. This means that energy sales are not lost but only managed wisely and therefore can the financial benefits be re-directed to all parties involved.

Significant lifestyle changes are not required by the end-user since the hot water cylinder will only be used as an energy-storage device and hot water will always be readily available due to the implementation of intelligent load-control-algorithms.

1.3.5 Water Heating As The Primary RDSM Option

According to Forlee [13], HWLC is expected to achieve the greatest impact in terms of load shifting and load reduction when compared to other RDSM options. This is due to the fact that in South Africa the hot water cylinder load is one of the largest contributors to residential demand and also coincides with the Eskom peak periods.

Experiments were conducted during 1997 on a national level to determine the effects of HWLC on the Eskom grid [13]. Reports claimed that in South Africa more than 600,000 households were under the control of load management-systems by the end of 1997.

The results of the experiments showed that under normal winter conditions the controllable hot water cylinder load available for control was in the order of 600 MW during the morning peak and 400 MW during the evening peak. Potentially 1.8 million hot water cylinders were in existence at that time which were not covered by load management systems. This adds up to 2.4 million controllable cylinders and extrapolates to an available load of 2.4 GW in the morning and 1.6 GW in the evening.

The implication is that with HWLC on it's own, it is possible to defer and even remove the need to build an additional generating plant. This will also ensure that the specifications set forth in the IEP6 will be met by making use of only HWLC, without even considering the large commercial and industrial market. Various HWLC-options are available and will be discussed in the following section.

1.4 HOT WATER LOAD-CONTROL OPTIONS

According to Van Harmelen and Van Tonder [5], thermal storage technologies in general use off-peak energy to supply on-peak demand for heating or cooling, and in the case of residential hot water, can use off-peak electrical energy to supply on-peak hot water. Control can either be in the form of decentralised - or centralised control.

1.4.1 Intelligent Control

"Intelligent" automated electronic systems are required when the selected control strategy is decentralised on a national level. The reason for that is twofold:

- The varying tariff due to the change in demand must be delivered in a timely fashion (e.g. every 24 hours) to the consumer.
- The customer then has to interpret this data and react on it to ensure some sort of saving, or even preventing penalties due to energy usage during peak times.

Clearly without automated control, this would be too much for the average person. The savings-to-capital-investment ratio is also not viable to leave the HWLC in the hands of the consumer.

The only advantage of decentralised HWLC is optimum customer-comfort. Implementing "intelligent" control algorithms centrally and taking all possible constraints into account can easily satisfy the same customer-comfort-levels.

1.4.2 Direct Control

The concept and application of HWLC is rather familiar as more than 30% of the nationally installed hot water cylinders are fitted with some sort of load management device [5]. Thus far, without failure, each of the studies that have investigated HWLC indicated optimal results from a direct load-control perspective [4].

It is eminent that direct control is going dominate the HWLC-market. The only problem is that no optimal solution has been defined and therefore should more attention be directed towards the rises and falls of the current HWLC-situation in South Africa.

1.5 THE SOUTH AFRICAN DIRECT CONTROL SCENARIO

Hot water cylinders have been the focus of several studies where they have been used as energy storage devices. As noted in the previous section, the main application was directed towards peak load shaving within device-interruption-base-load-management programs. The general public have not been properly informed about the advantages of these schemes and therefore has HWLC been negatively interpreted [4].

The initial idea of HWLC was not to infringe in any way on the customer-comfort-levels but thus far to the knowledge of the author, there exist no solution that mutually satisfies the needs of the:

- Utility,
- Municipality and
- Residential consumer.

Various authors have examined the individual needs of the three entities and some key objectives are described in the following paragraphs.

1.5.1 Utility Objectives

From a utility's perspective, a load management-system has to be designed and evaluated so that a group of residences may be used to [4]:

- Implement the least cost and risk solutions to obtain a balance in the demand versus supply equation.
- Positively contribute towards regulatory and environmental pressures by employing energy conservation - and energy efficiency programs.
- Build customer loyalty by offering more customised products and services.
- Employ load-control options as suitable and reliable emergency load-shedding mechanisms.
- Reduce the risk of any possible losses.
- Constantly improve their system utilisation and efficiency.

Currently there are two options from which Eskom can enforce these objectives by means of HWLC:

Eskom HWLC-systems

Various residential areas in South Africa are privately reticulated and directly supplied by Eskom. This means that the residential consumer receives an electricity bill directly from Eskom and not from a local municipality. In these areas Eskom are entitled to install their own HWLC-system and directly influence the national demand load-profile.

Tariff Structures

Municipalities throughout South Africa have conventionally been billed by the utility according to demand charge tariffs that consisted of two parts [14]:

- **Demand Charge:** Payable for each kilovolt ampere (kVA) or kilowatt (kW) of the maximum demand supplied during the month. It is calculated by integrating the measured demand over half-hourly period for kVA measured supplies or hourly periods for kW measured supplies. No demand charge is applicable during off-peak periods. Where a kW charge is applicable, the power factor under all loading conditions shall not be less than 0,85 lagging and shall not lead under any circumstances.
- **Active Energy Charge:** A fixed charge for each kilowatt-hour (kWh) of active energy consumed.

The idea of using a tariff structure as a secondary DSM control method is to use pricing signals to indicate the national peak-demand periods. The expensive energy rates during these high demand periods must force municipalities to alter their controllable load in order to ensure optimal savings on their utility bill. Needless to say this is not the case in South Africa. During the Domestic Use of Electrical Energy (DUEE) conference in 1998, Van Harmelen [5] noted some problems encountered with the demand charge tariff as conventional tariff, which would be described in detail in section 1.8.2.

TOU-tariffs were initially appropriate for customers who are able to manage their energy consumption and maximum demand according to the utility's specified time schedule. Lately the utility is making TOU-tariffs more attractable for municipalities in order to force them to reduce energy consumption during national peak times and not municipal peak times.

A TOU-tariff also consists of the same two components found in demand charge tariffs. The only difference is that the active energy is no longer calculated at a fixed rate but rather on a variable rate according to the national supply and demand ratio. Megaflex is a typical TOU-tariff implemented in South Africa with its various time periods illustrated in figure 1.4.

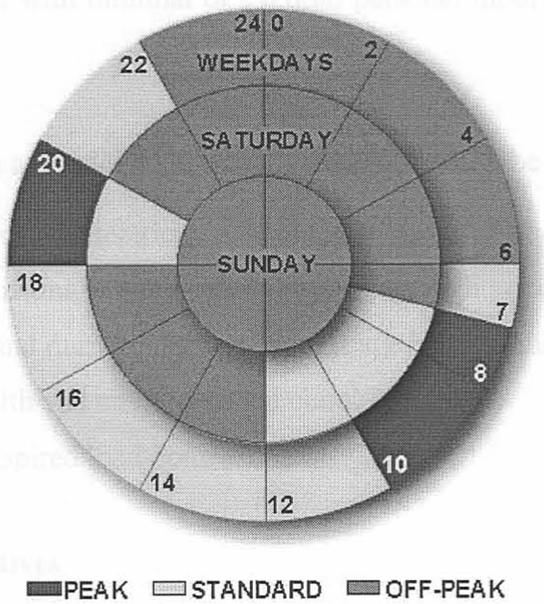

Figure 1.4: Megaflex time periods implemented during the calendar year of 2001 [14].

The advantage of using a TOU-tariff is that money can be saved even when the municipal load-profile exhibits a commercial nature rather than a residential footprint [15]. A demand charge tariff would have been less effective for commercial clients tend to peak between 10:00 and 15:00. This is exactly the time when the minimum amount of hot water energy is available for reducing the MD and therefore little hot water energy is shifted out of the national peak periods. With the TOU-tariff these municipalities can save more by shifting their hot water load out of the national peak periods than controlling their commercial MD during midday. Municipalities with an uncontrolled load factor close to unity can also benefit in the same way.

The disadvantage of shifting energy is that it requires a much more complex load shifting algorithm that will ensure the readily availability of hot water to the residential customer. It must also be done everyday in contrast with the less frequent shedding caused by a demand charge tariff.

1.5.2 Municipality Objectives

Municipalities are also investing private capital in their own load-control systems. Their primary aim is to minimise the utility bill according to the applicable tariff structure with secondary spin-offs such as switchgear over current protection. The control algorithms must be able to function with minimal or even no personal input while providing optimal results.

Control algorithms from a municipal perspective should ideally be designed to [4]:

- Reduce the overall cost of electricity – resulting in lower utility bills.
- Make pro-active decisions in anticipation of possible high priced periods.
- Save energy before and during periods of low usage by minimising losses.
- Improve general health and environmental conditions.
- Respond to utility inspired load-control signals.

1.5.3 Consumer Objectives

The South African HWLC-systems hardly cater for the actual needs of the consumer. These needs include [4]:

- To reduce the overall cost of electricity after installation of the load-control device.
- Make pro-active decisions in anticipation of expected excessive appliance usage.
- Incorporate residence design and safety constraints into the appliance.
- Save energy before and during periods of low usage by minimising losses.
- Improve or sustain existing comfort-levels as set before implementation of control algorithms.
- Additional savings when comfort-levels were infringed [15].

Generally HWLC-systems also ignores the impact and effect on the individual customer's

- Behaviour,
- Preferences,
- Living conditions and
- Reaction after installation and implementation.

Some load management systems require user information regarding water usage patterns, amount of users per cylinder, water temperature, etc. The information is then used to divide the users into specific groups and then prioritised accordingly for load shedding and restoring sequences. When the municipality decides to drive the system beyond the customer-comfort-levels, all the groups will end up with cold water during the day, making any form sequencing frivolous.

The current HWLC-strategies are neither optimal nor customer orientated therefore must one take a closer look at the effects of human behaviour on the national and local grid in order to design a more customer orientated HWLC-system.

1.6 EFFECTS OF HUMAN BEHAVIOUR ON THE NATIONAL LOAD-PROFILE

It must be kept in mind that a DSM program will influence a consumer's behaviour. It is crucial to understand the consumer's behaviour during the three broad phases of a DSM program [9]:

- **Before implementation:** To understand consumer behaviour and - usage.
- **During implementation:** To predict the rate of market penetration of the DSM program as well as the market penetration of the energy-consuming appliance and or - behaviour.
- **After implementation:** To determine the long-term value of the DSM intervention in terms of the market position and system load-profile.

The following paragraphs are based on the results published by Vermaak [7] regarding consumer behaviour before HWLC-implementation. The change of consumer behaviour after implementation can be restricted if the system is operated in a customer-friendly manner by minimising the risk of cold water when the client expects to receive hot water. The dynamics of hot HWLC must be modulated and examined to determine the effect of load-control on the demand of a national - or municipal system.

1.6.1 Weekly Patterns In Human Behaviour

Figure 1.5 depicts the load-profile for a typical week on the Eskom grid. Each day is characterised by the two prominent peaks:

- The morning peak between 8:00 and 10:00 and
- The evening peak between 18:00 and 20:00.

These peaks are almost solely due to residential activities in the domestic sector and can be verified by the peak on Sunday-mornings at 11:00. On the other hand the deep are due to the commercial and industrial sectors closing at nighttime when the load mainly comprises of critical consumers and very large industrial customers.

As expected, the load-profiles for weekdays from Tuesday to Thursday are almost the same due to similar human behaviour on these days. People tend to be reluctant to work at full capacity during Monday mornings, resulting in a lower peak. The peak on a Friday morning is standard but lower in the evening as result of the smaller commercial and industrial companies ending off their work for the week. This is also eminent in the continuous dropping of the load during Saturdays.

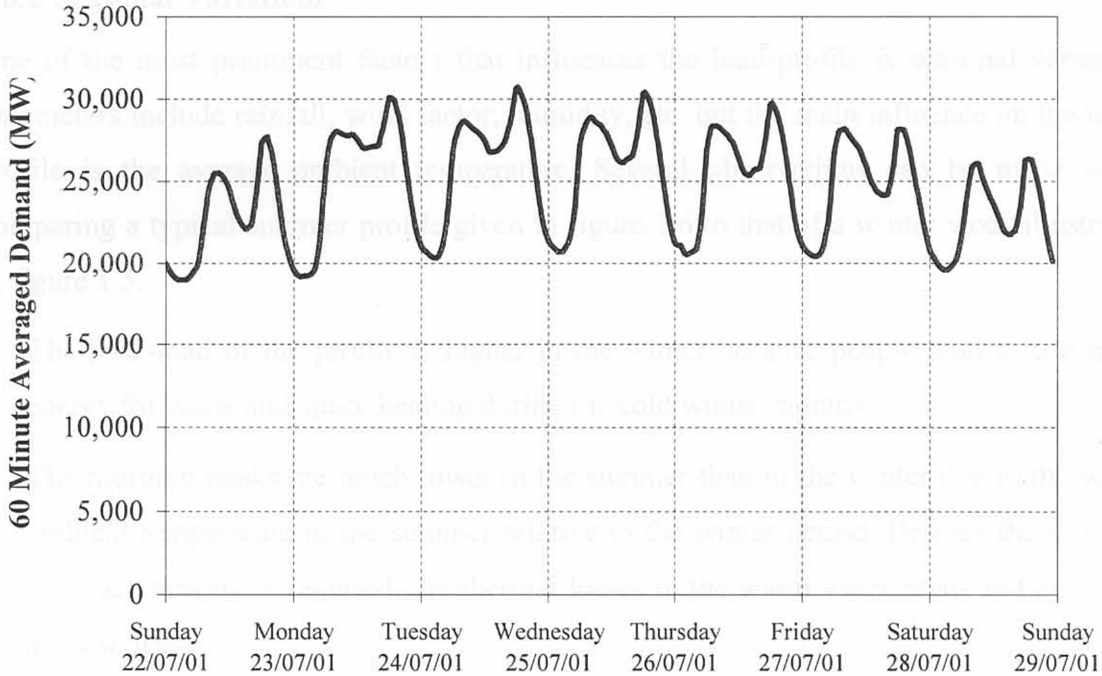

Figure 1.5: Eskom national load-profile for the week stating on Sunday, 22 July 2001.

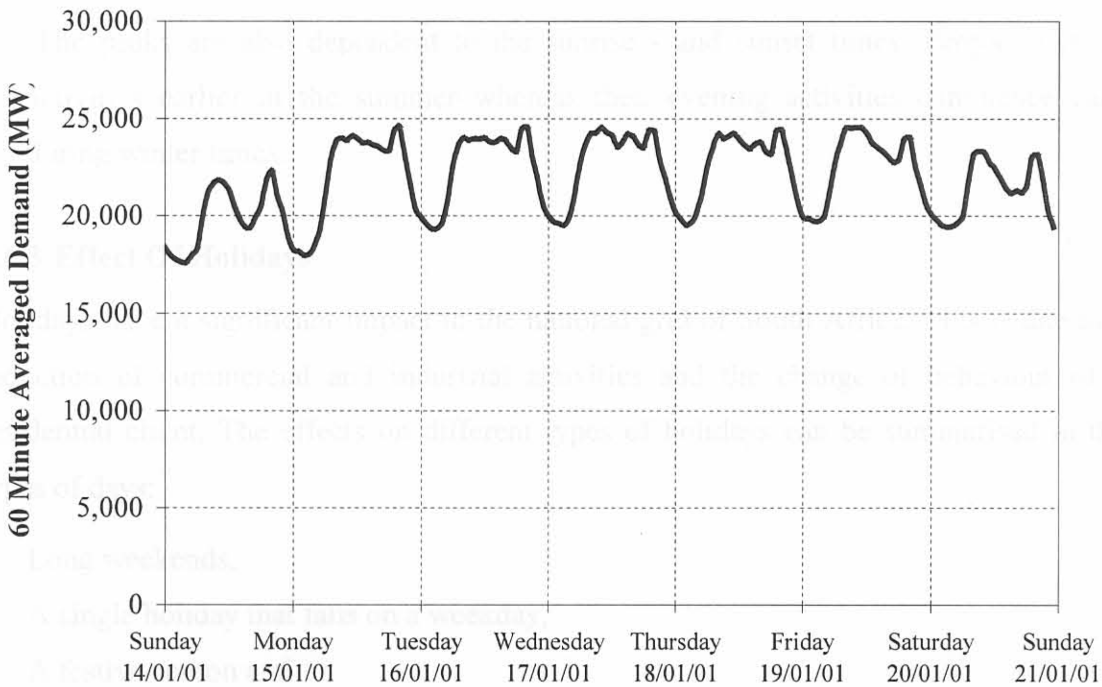

Figure 1.6: Eskom national load-profile for the week starting on Sunday, 14 January 2000.

1.6.2 Seasonal Variations

One of the most prominent factors that influences the load-profile is seasonal variation. Parameters include rainfall, wind factor, humidity, etc. but the main influence on the load-profile is the average ambient temperature. Several observations can be made when comparing a typical summer profile given in figure 1.6 to that of a winter week illustrated in figure 1.5.

- The base-load of the profile is higher in the winter because people tend to use more energy for water and space heating during the cold winter months.
- The morning peaks are much lower in the summer than in the winter due to the warm ambient temperature in the summer relative to the winter period. Besides the fact that no space heating is required, the thermal losses in the warm water pipes and cylinders are also less.
- The commercial air conditioning systems are almost continuously running during the warm summer months. Space heating does not bring about the same reaction during the winter season because it is required during the evenings and not during daytime.
- The peaks are also dependent to the sunrise - and sunset times. People start their activities earlier in the summer whereas their evening activities commence earlier during winter times.

1.6.3 Effect Of Holidays

Holidays have a significant impact in the national grid of South Africa. This is due to the reduction of commercial and industrial activities and the change of behaviour of the residential client. The effects on different types of holidays can be summarised in three types of days:

- Long weekends,
- A single holiday that falls on a weekday,
- A festive season and
- Special events.

Long Weekends

Long weekends are characterised by relatively low energy consumption throughout the course of the weekend and can be estimated as if it was a Sunday. The days before and after the long weekend exhibit the same characteristics found on regular Fridays and Mondays.

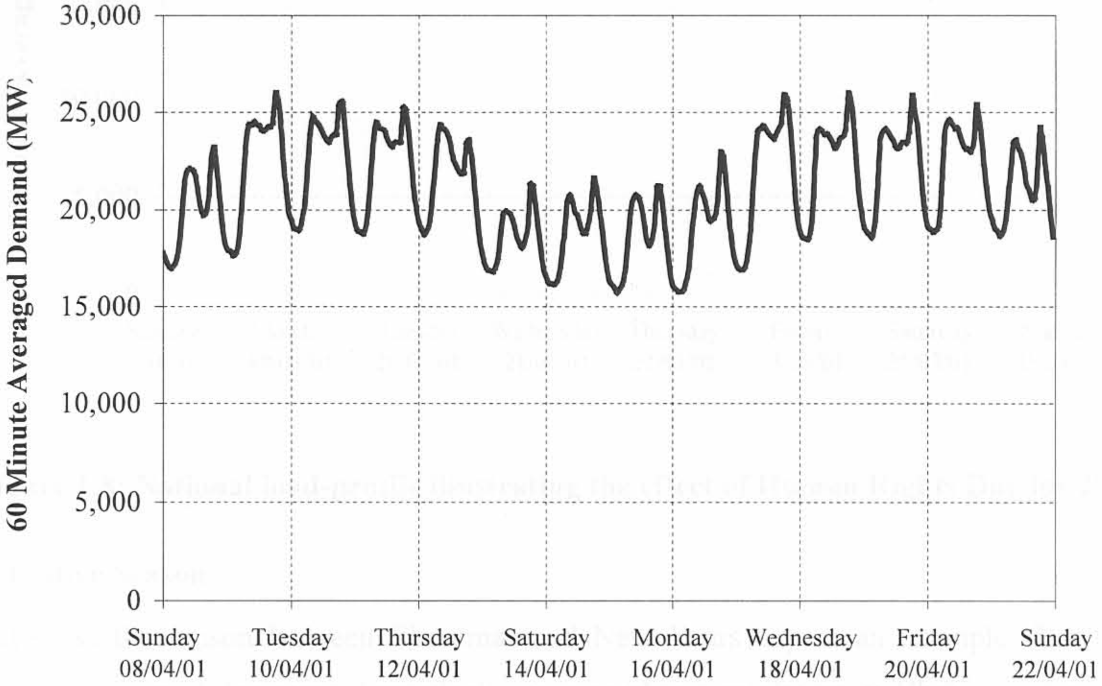

Figure 1.7: Two-week national load-profile for Easter weekend.

The example shown in figure 1.7, clearly illustrates the difference between a regular and a long weekend. During 2001 Easter holiday was celebrated on Friday, 13 April along with Family Day on Monday, 16 April. Notice the residential peak on Monday evening due to people returning from their holiday destinations.

A Single Holiday That Falls On A Weekday

Days like these tend to have a minimal load-effect on the immediate preceding and subsequent days. The holiday itself can again be estimated as a Sunday.

During 2001, Human Rights Day was celebrated on a Wednesday and the consumption was typical of the regular Sunday consumption pattern. It is also noticeable that Tuesday and Thursday were unaffected by the public holiday.

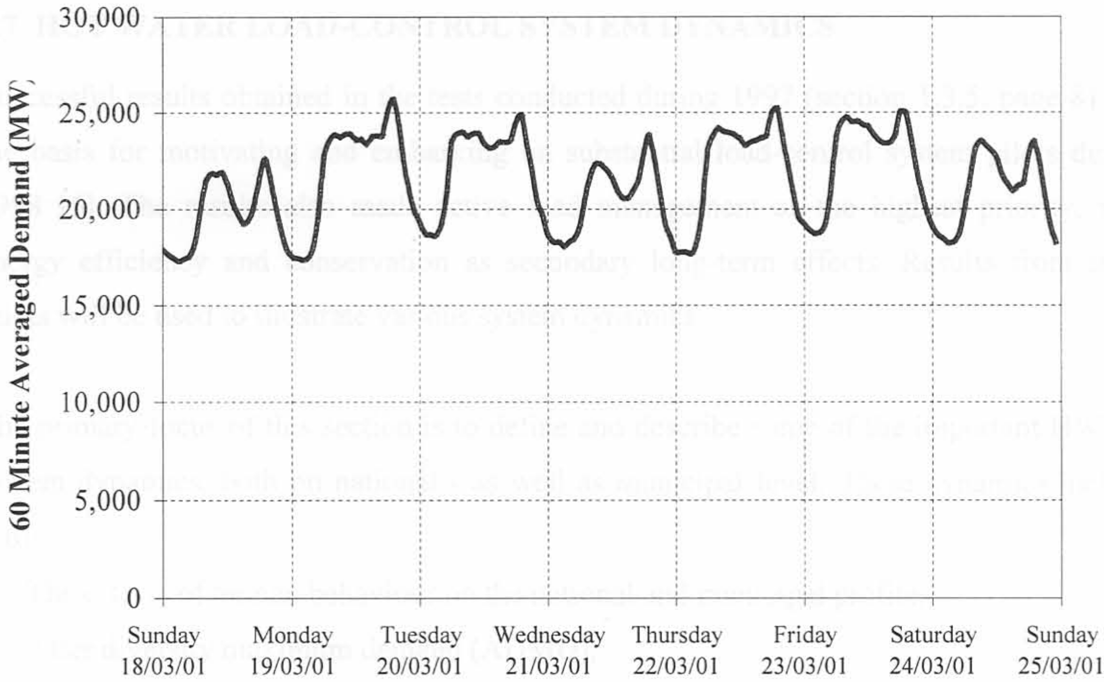

Figure 1.8: National load-profile illustrating the effect of Human Rights Day for 2001.

A Festive Season

Let's use the season between Christmas and New Years day as an example. The total energy consumed decreases dramatically as it reaches a minimum at Christmas day. The shape of the load follows the trend of a regular week, but with a smaller base-load. It only recovers after New Years day when the industrial - and commercial activities commence.

1.6.4 Special Events

Special events such as the election in 1994, natural disasters, strikes, etc. can all have an effect on the national load-profile. For example the load-profile on Election Day took the shape of a Sunday, but each special event must be taken on it's own credit and handled individually.

The effects of human behaviour must be taken into account when developing control algorithms; accentuating the importance of knowing the user-patterns before and after DSM-installation.

1.7 HOT WATER LOAD-CONTROL SYSTEM DYNAMICS

Successful results obtained in the tests conducted during 1997 (section 1.3.5, page 8) laid the basis for motivating and embarking on substantial load-control system pilots during 1998 [5]. The results also made active load management as the highest priority, with energy efficiency and conservation as secondary long-term effects. Results from these pilots will be used to illustrate various system dynamics.

The primary focus of this section is to define and describe some of the important HWLC-system dynamics, both on national - as well as municipal level. These dynamics include [16]:

- The effects of human behaviour on the national and municipal profile,
- After diversity maximum demand (ADMD),
- Cold-load pickup,
- Risk of cold water and
- Tariff structures.

Accurate models can be generated to simulate different scenarios once the dynamics of HWLC are fully understood. These simulations can then be used to optimise HWLC on a national level with end-user comfort taken into account.

1.7.1 Notch Testing

As noted previously, the 1997 tests were conducted to calculate the contribution of hot water cylinder consumption to the national demand of South Africa [13]. The study included the selection of 12 municipalities with operational load-control systems and these municipalities had to be a fair representation of the national demand. The load-control systems were then used simultaneously in various tests to determine the contribution of the hot water load within the controlled areas.

One of the tests involved switching all the load-control devices OFF on the half-hour for five minutes and then returned the supply back to the cylinder elements afterwards. The mere fact that the supply to a device was restored doesn't mean that the specific hot water cylinder withdrew current at that point in time. The assumption was that only the cylinders that withdrew current before the 5-minute notch interval would continue to do so again after the supply has been restored. The resultant "notch" value in the load-profile is then an accurate representation of the hot water load at that time and is referred to as the Total After Diversity Maximum Demand (TADMD).

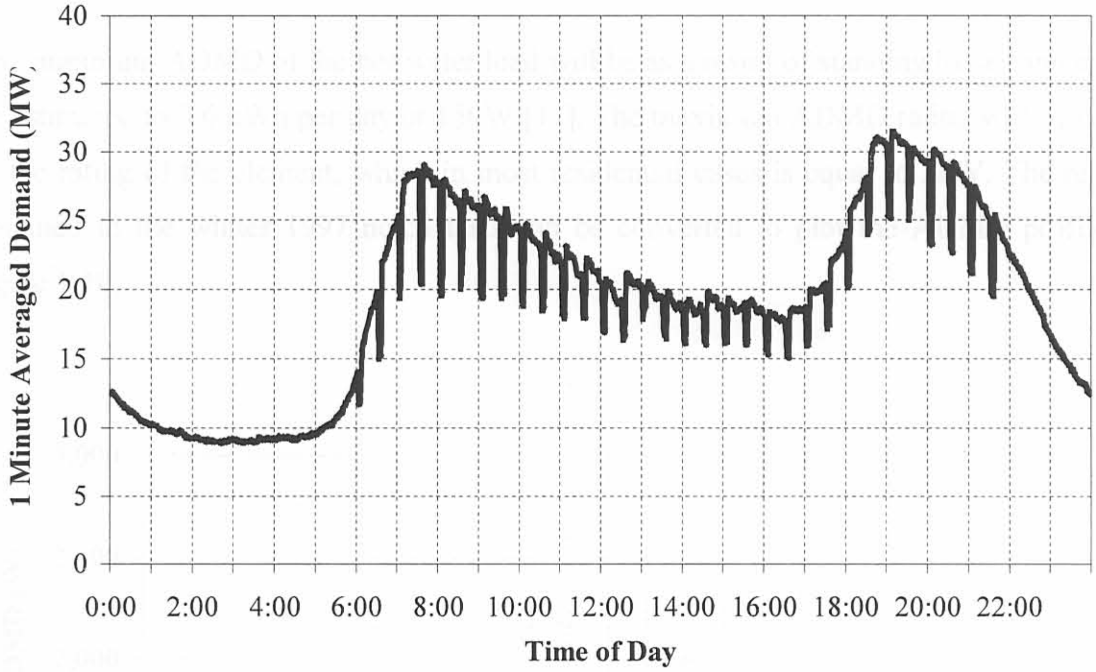

Figure 1.9: Example of notch test results.

These tests were conducted during all four seasons to determine the seasonal water-heating consumption patterns.

1.7.2 After Diversity Maximum Demand

The After Diversity Maximum Demand (ADMD) for a specific system can be described as the total electrical load per installed relay that can be controlled by the system at a certain time of day.

$$\text{TADMD} = \text{Total Load} - \text{Uncontrollable Load} \quad (1.1)$$

$$\text{ADMD} = \text{Total ADMD} \,/\, \text{Installed Relays} \quad (1.2)$$

The minimum ADMD of the hot water load will be as a result of standing losses and could be estimated to 3.6 kWh per day or 150W [17]. The maximum ADMD rating will be equal to the rating of the element, which in most residential cases is equal to 3kW. The results obtained in the winter 1997 notch tests can be converted to plot the ADMD profile in figure 1.10.

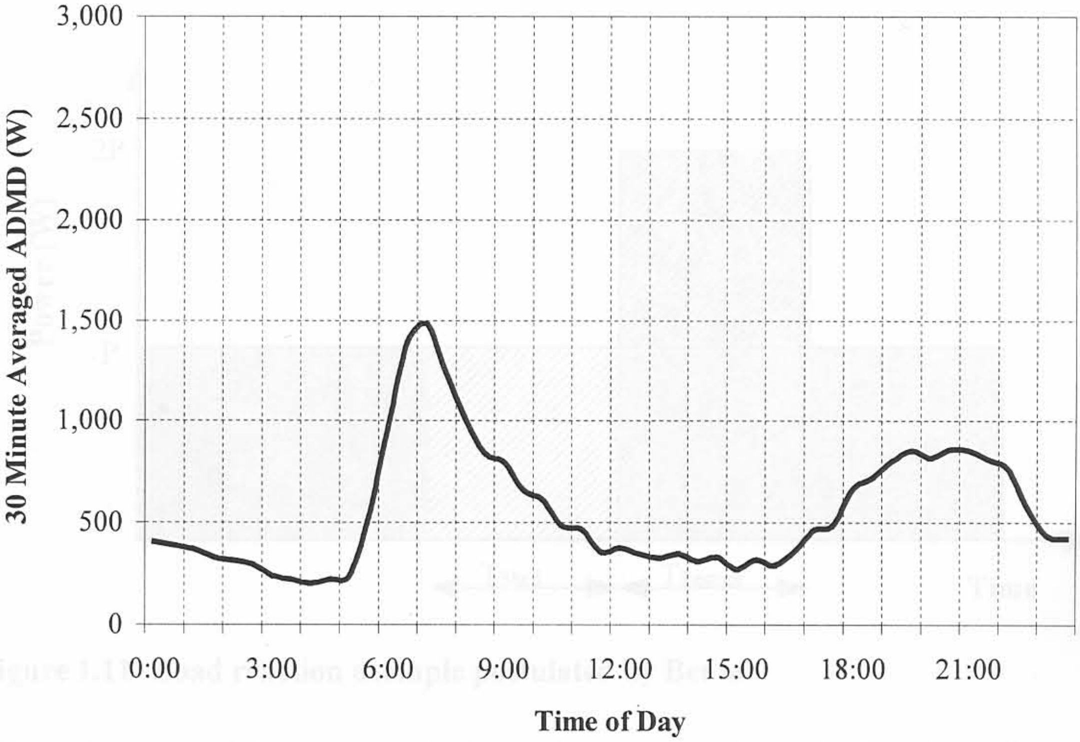

Figure 1.10: South African winter ADMD profile [13].

The profitability of an HWLC-system is determined by the amount of load per relay that can be shifted at a certain time of day. Therefore must one keep in mind that the amount of functional relays is more important than the amount of installed relays when calculating the total load available for shifting purposes.

Calculations based on the ADMD are very useful for load management purposes since it is independent of future reactions of the uncontrollable - or base-load [15]. The savings calculation requires the reconstruction of the uncontrolled load-profile and this is also made possible by the ADMD data. Reconstruction is usually done after the control has been applied but it is possible to predict the way in which the load is going to react to the load-control actions as well.

1.7.3 Load Reaction

Beute [18] was one of the pioneers in the study of the effects of HWLC on the national load-profile. He postulated that the same amount of energy extracted during load-control would return immediately after the load has been restored, with the same shape as original extraction. The implications of this postulate are presented by example in figure 1.11.

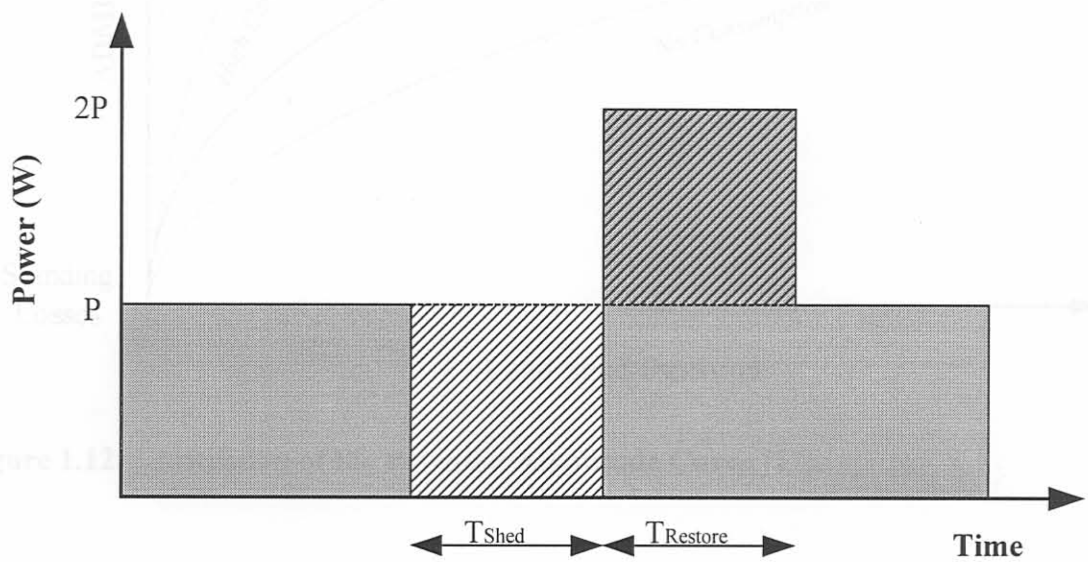

Figure 1.11: Load reaction example postulated by Beute.

Although some of Beute's results have been proven inconclusive, he still laid the foundation for modern day research in the field of load reaction.

At the turn of the century, Calmeyer [17] claimed that when load is shed, the potential of the peak that will be caused when the load is restored increases *exponentially* with time and defined it as the Potential Amplitude Curve. Calmeyer has shown no concrete proof of his claim and thus as far as it could be established no analytical relationship has been derived for this phenomenon.

According to him, the curve is mainly dependent on the following factors:

- The ambient air-temperature and cylinder heat-loss factor,
- The thermostat setting of the hot water cylinder,
- The temperature of the inlet water and
- The rate of consumption of hot water from the cylinder.

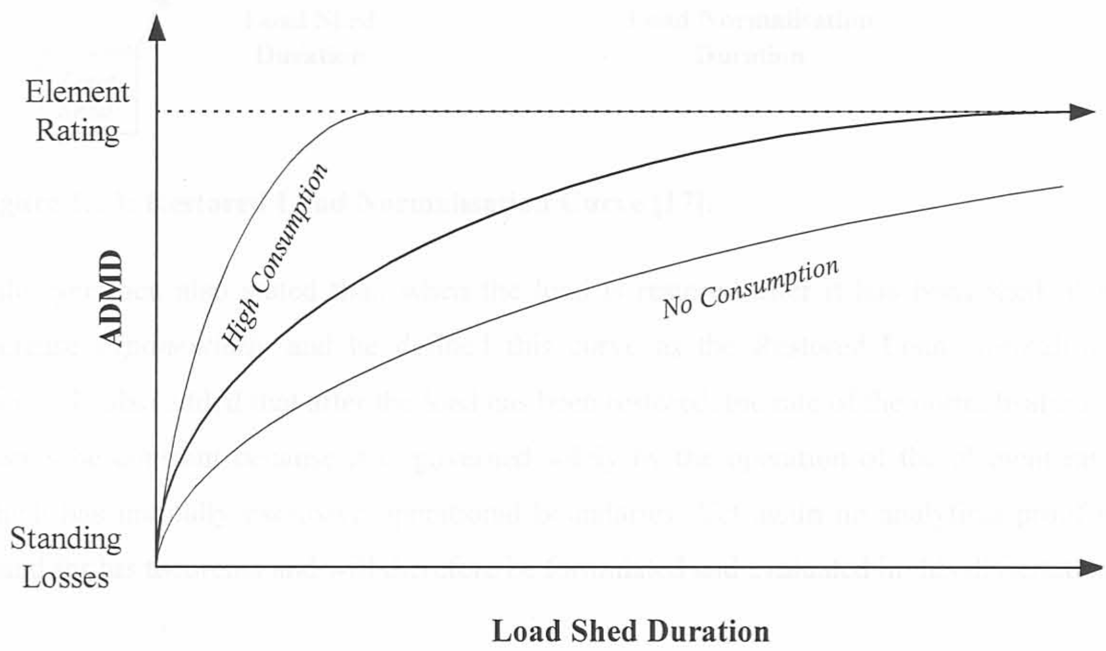

Figure 1.12: Illustration of the Potential Amplitude Curve [17].

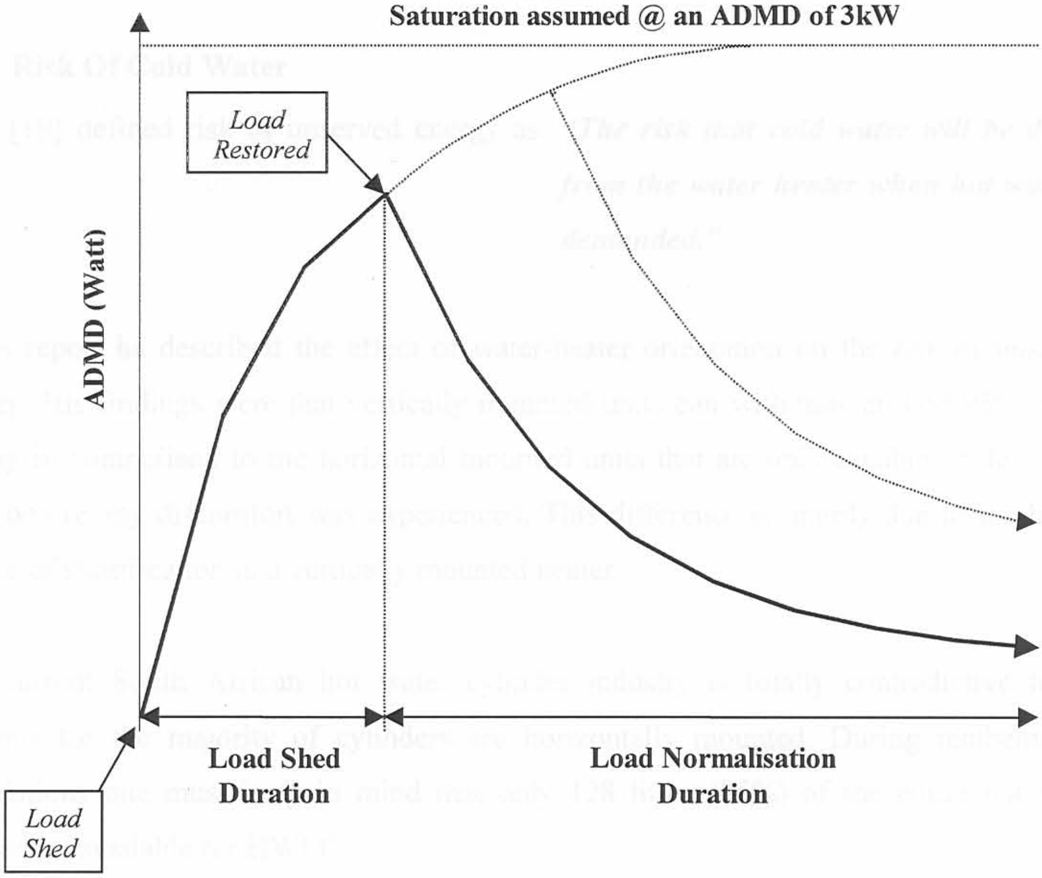

Figure 1.13: Restored Load Normalisation Curve [17].

Calmeyer then also stated that, when the load is restored after it has been shed, it will decrease *exponentially* and he defined this curve as the Restored Load Normalisation curve. He also added that after the load has been restored, the rate of the normalisation will always be constant because it is governed solely by the operation of the element rating, which has mutually exclusive operational boundaries. Yet again no analytical proof was found for his theorems and will therefore be formulated and evaluated in this dissertation.

1.7.4 Risk Of Cold Water

Smit [19] defined risk of unserved energy as: ***"The risk that cold water will be drawn from the water heater when hot water is demanded."***

In his report he described the effect of water-heater orientation on the risk of unserved energy. His findings were that vertically mounted units can withdraw around 95% of the energy in comparison to the horizontal mounted units that are only capable of delivering 85% before any discomfort was experienced. This difference is mainly due to the higher degree of stratification in a vertically mounted heater.

The current South African hot water cylinder industry is totally contradictive to his findings for the majority of cylinders are horizontally mounted. During mathematical calculations one must keep in mind that only 128 litres (85%) of the entire hot water cylinder is available for HWLC.

1.7.5 Influence Of Tariffs On Load-Control Algorithms

A change in the tariff structure will directly influence the outcome and control strategies of a municipal hot water load-controller. As described in section 1.5.2, the primary objective of a municipal hot water load-controller is to minimise the utility bill.

HWLC has been the saving hero of several municipalities, but at a price. On the physical layer HWLC is a minefield and one needs to understand the installation environment as well as the mathematical simulations to create a fully functional system. To understand this process one must take a look at the deficiencies encountered by existing hot water load-controllers in general.

1.8 DEFICIENCIES OF EXISTING HOT WATER LOAD-CONTROLLERS

One cannot design a HWLC-system on the basis of the system dynamics alone. Various authors [4] have studied the mathematical side of HWLC intensively but have paid little or even no attention to the physical installation and implementation of these control systems. This section elaborates on the deficiencies found in the existing HWLC-market and should be read in junction with the problems discussed in the previous section.

1.8.1 Open Loop Control

Currently in South Africa the load-control market is totally dominated by the specific tariff that each municipality is billed according to. Control is only done from the top downwards and the residential customers have little or no say about when they would prefer to have hot water. For example, certain customers prefer to shower during the morning peak period while others prefer to shower later in the evening. These customers are willing to set aside their warm water load for control purposes, only at different times of the day.

1.8.2 Incorrect Influence Of Tariff Structure

Problems have been encountered with municipalities who have already installed HWLC-systems. The drawback is the co-ordination of load shifting efforts of the municipalities with that of the need of the supplier. The one option is that the utility must be in total control of the entire controllable hot water load. This is ideal but the politics in terms of incentives towards both the municipality and residential end-user will always be a problem.

The other option is to improve the pricing signals from the supplier. These signals must be strong enough to "force" the municipality to conform to the needs of the national demand [16]. New tariffs should be structured so that both utility and municipality could benefit from HWLC.

During the DUEE conference in 1998, Van Harmelen [5] noted some problems encountered with demand charge tariffs when used as HWLC-pricing signals. The main problem was the co-ordination of the HWLC-efforts on a national level since local municipal conditions seldom reflect national grid conditions. The inverse effect was also noted: The national supplier could not benefit from the surplus energy available when a municipal HWLC-system is inactive.

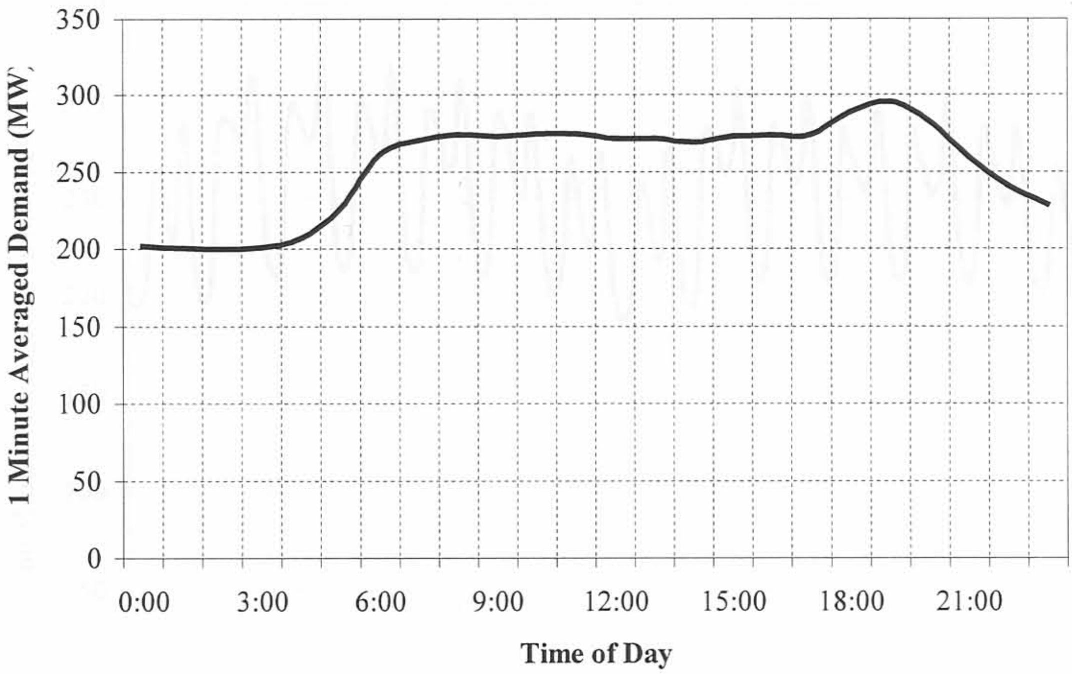

Figure 1.14: Winter load-profile only requiring control from 18:00 to 21:00.

In the winter seasons most of the residential load-profiles are peaking in the evenings. The optimum set point is then adjusted in order to control the load in terms of a minimum MD. This results in controlling only the evening load and minimum, if any, control is applied to the morning load.

If the load-profile in figure 1.14 was controlled on a demand charge tariff, control would have only been applied between 18:00 and 21:00. The lack of control during the morning period is an example of surplus energy going to waste.

The monthly billing nature regarding the MD for demand charge tariffs is extremely negative regarding optimal load-control on a national level. Once the specific month's MD set point has been exceeded the load-controller automatically adjusts the control set point to the new MD value. The municipality is going to pay for the new MD value, so it is frivolous to control the load on a lower MD; leading to optimal control only for certain days in the month.

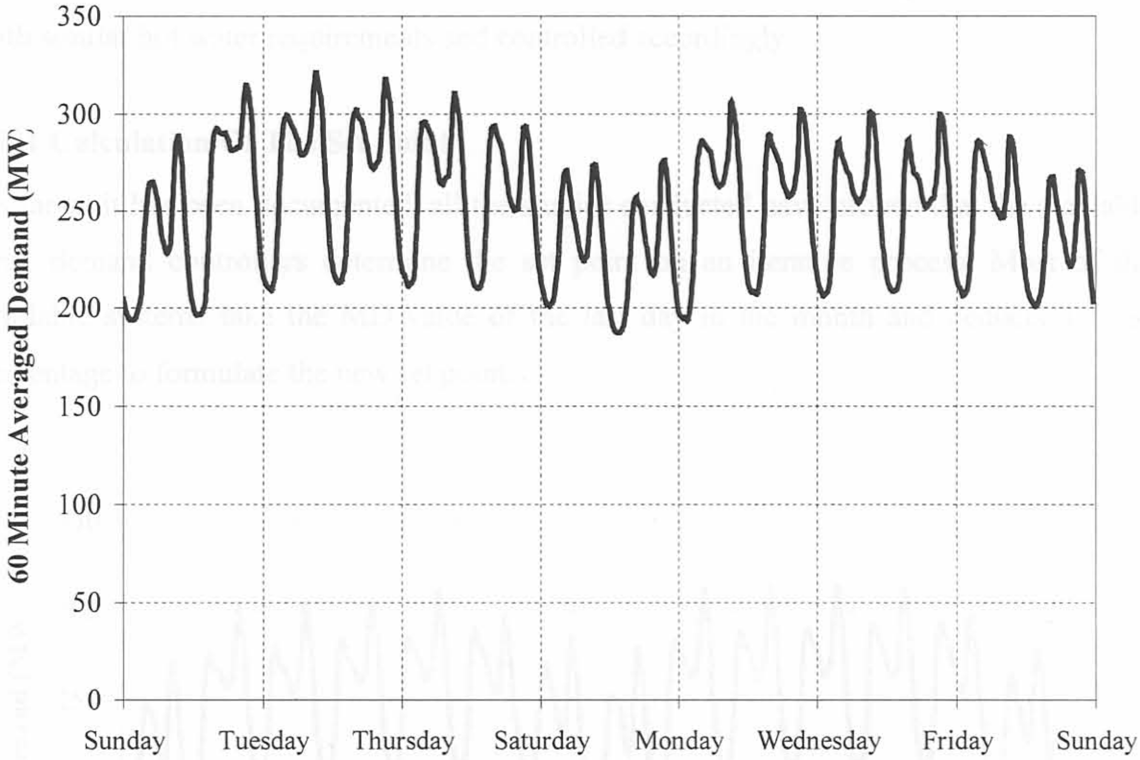

Figure 1.15: Load-profile requiring minimal MD control during the second week.

The situation depicted in figure 1.15 is a typical municipal load-profile. Say for instance the shed-level was set at 300 MW for this particular month. Control would only be applied when the demand overshoots the set point, which in this case would happen on:

- Both Mondays and
- The first Tuesday, Wednesday and Thursday.

When charged according to a demand charge tariff there exists no incentive to motivate any control on the other days illustrated, even if the utility had a desperate need for surplus energy during the uncontrolled days.

1.8.3 Human Behaviour

As described in section 1.6, human behaviour can have predictable outcomes regarding energy management. These behaviours have been neglected in the past and this has definitely led to customer discomfort. Residential users need to be categorised into groups with similar hot water requirements and controlled accordingly.

1.8.4 Calculation Of The Set Point

As far as it has been documented, all the studies conducted have proven that the available peak demand controllers determine the set point on an iterative process. Most of the available systems take the MD value of the last day in the month and deducts a fixed percentage to formulate the new set point.

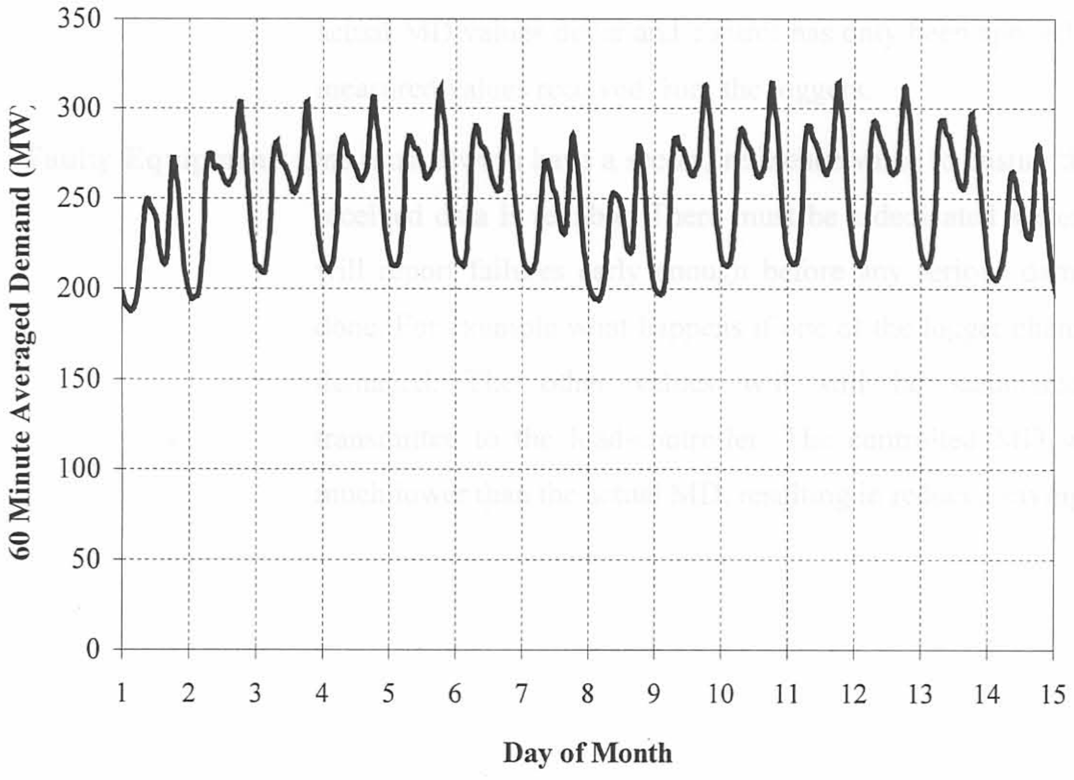

Figure 1.16: Load-profile for the first 2 weeks in June.

Say for instance the MD for the last day in May on figure 1.16 was 280 MW. The controller will then select the shed-level 5% lower (265 MW) in June to force optimal savings on the supply-side. In general, the load tends to pick up towards the winter months, as illustrated by the second week. This increase causes the load to exceed the 265 MW set value and forces the controller to adjust the shed-level to 295 MW.

In this case the controller removed a load of up to 30 MW unnecessarily throughout the first week. This would not have been the case if the controller was able to predict the MD for June more accurately. It is recommended to invest in an expert set point calculation system to improve customer orientated control.

1.8.5 Reliable Data

Reliable data is of utmost importance to ensure optimum control. Data must be timely, accurate and relevant. From personal experience [15] and similar case studies examined the following problems occurred with data collection:

- **Incorrect CT-ratio:** This can often lead to numerous court cases. The measured and actual MD values differ and control has only been applied to the measured values received from the loggers.
- **Faulty Equipment:** One must always have a second reference value to ensure that the received data is reliable. There must be a dedicated system that will report failures early enough before any serious damage is done. For example what happens if one of the logger channels is damaged. The other values will still be summated and transmitted to the load-controller. The controlled MD will be much lower than the actual MD, resulting in reduced savings.

- **Communication Layer:** The communication link between the measuring nodes and the central station is the most crucial component of a load-control system. The link must be fast enough to ensure that the data arrives in time and also reliable to maintain a low error rate. Once the communication link is down, gaps in the data will occur, making it impossible to control accurately. In extreme cases the entire available load has to be shed in order to minimise the unknown MD.

- **Relevant Data:** It is no use to receive only kW data when the tariff is calculated on a kVA basis except at unity power factor.

- **Synchronisation:** Generally in South Africa, the MD is calculated over a half-hour integration period. This means that the load-control equipment must be synchronised with the supplier's equipment to ensure correct measurement over the same integration period. Cases have been recorded where the supplier and municipality had a drift in synchronisation of more than 15 minutes. Needless to say it has led to catastrophic disputes.

1.9 OBJECTIVES

Several research activities confirmed that it is possible to design controllers that are able to provide simultaneous benefits to all parties. According to Van Harmelen [4], various authors have also demonstrated the feasibility of automated HWLC-systems without any customer intervention to operate them.

The ideal is thus to bring forth automated controllers that are able to automatically adapt themselves according to changing consumer needs whilst optimising the system holistically from a utility or municipal perspective.

There are three parties involved in the HWLC-process:

- A Utility,
- Municipalities and
- Residential consumers, each with specific influences on the system.

When designing an optimal HWLC-system, all three parties must be considered and a successful solution should include mutual benefit to all.

1.9.1 Main Objective

The main focus of the dissertation is then primarily to facilitate the process of implementing non-existing technology to advocate consumer needs whilst assisting system optimisation on a national level from a municipal perspective.

1.9.2 Specific Objectives

Chapter 1 has confirmed that HWLC is definitely not a new concept to South Africa. The diversity of installation requirements, as well as the availability of various types of HWLC-systems defies the object of dedicating the research to a specific hardware - or control configuration.

In this dissertation the primary objective is to formulate an energy policy in terms of an end-user model that is capable of using the diversity within the consumer behaviour to its advantage. The model must be applicable to existing technology but compatible with future inventions.

The secondary objective is to develop techniques that will enable municipalities to forecast their electricity demand due to hot water load management strategies taken. With these techniques in hand, the municipality has the ability to act on pricing signals rather than react on load levels. This will enable them to alter the shape of their load-profiles in such a way to suit their electricity tariff and thus minimising the electricity bill at the end of the month.

The third and final objective is to develop models that would assist the consumer orientated control strategy in:

- Estimating the average temperature of the controlled hot water cylinders and to
- Formulate a feasible and auditable savings distribution strategy.

These objectives must then be simulated, realised and evaluated in a working environment similar to that of a municipality.

1.10 OUTLINE

At the end of the day the residential consumer must trust the installed HWLC-system. If customer-comfort-levels are neglected, the user will find ways to bypass the load control device. This will eventually generate a snowball-effect and only the honest customers will be penalised.

The incentives must also be rewarding for the residential user for some discomfort experienced at times. This reward will make him feel "important" in the scheme of things. The primary objective is thus to modulate a load-control system that will differentiate between various consumer usage-patterns while attending to preferable comfort-levels.

In general the modulation and system dynamics on both national and municipal levels have been discussed in chapter 1. The objective from now on is to pioneer the foundation work for customer-orientated control.

Chapter 2 will examine HWLC in South Africa holistically and development will be done from the top down. Once the national system requirements have been defined, the focus can be narrowed down to compensate for customer behaviour and then finally meet the residential customer's needs in terms of comfort-levels and incentives.

Complex mathematical requirements encountered in chapter 2, will be solved individually in chapter 3. Development will either be done by illustrative examples or derived from basic principles. Case studies will also accompany each model developed to illustrate the integration process and to verify the results within a physical environment.

The heart of this dissertation is founded on the knowledge and experience gained over a research period of three years at the University of Pretoria. The road to optimal HWLC is a constant wander in an undiscovered pathway. Almost like Thomas Edison, it is more a struggle to eliminate the impossible to find the possible. Chapter 4 will take a closer look at the successful results obtained to date with the HWLC-system installed at the University of Pretoria.

Finally chapter 5 will be dedicated to conclude the research done in this dissertation and to recommend possible future research areas for model improvement.