CUSTOMER-ORIENTATED HOT WATER LOAD MANAGEMENT

by

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“FOR THE LORD GIVES WISDOM,

AND FROM HIS MOUTH COMES

KNOWLEDGE AND

UNDERSTANDING.”

- Proverbs 2:6 -

ABSTRACT

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The reader will be introduced to the South African electrification crisis and the benchmarks set by Eskom to contain this problem. Various load management options will be discussed but the work done throughout this dissertation is to direct the attention towards the possibility of implementing a customer orientated hot water load control system. Various authors have studied ways to solve the problems found in the South African hot water load control scenario, but their "optimum" control strategy hardly included the needs of the end user.

Research areas include:

- Hot water load control seen from a national perspective,
- A customer-orientated hot water load management methodology designed to satisfy the mutual needs of the utility, municipality and residential consumer,
- Hot water load control system dynamics,
- Average cylinder temperature prediction and
- Savings calculation and distribution.

It is inevitable that some emotions would be stirred when the paradigms starts to shift towards consumer-orientated control, but something has to be done to change the current situation.

Keywords: Hot water load control, cold-load pickup, hot water cylinder temperature, effects of human behaviour, savings distribution.

OPSOMMING

Outeur: A.S. Wilken

Studie Leier: Prof. G.J. Delport

Die leser sal bekend gestel word aan die Suid-Afrikaanse-elektrifiserings-krisis en die doelstellings wat deur Eskom daar gestel is om die probleem te oorbrug. Die bespreking word ingelei deur 'n verskeidenheid lasbeheer opsies te bespreek wat dan uitloop in die implimentering van 'n kliënt-gebaseerde-warm-water-lasbeheer-metodiek. Verskeie studies is oor die jare geloots om die Suid-Afrikaanse warm-water-lasbeheer situasie op te los, maar geen optimale oplossing het die behoeftes van die residensiële kliënt ook in ag geneem nie.

Navorsing sluit onder andere die volgende areas in:

- Nasionale perspektief oor warm-water-lasbeheer,
- Kliënt-gebaseerde-warm-water-lasbeheer-metodiek wat ontwerp is om die behoeftes van die elektrisiteitsvoorsiener, munisipaliteit en residensiële kliënt gemeenskaplik te bevredig,
- Dinamika agter warm-water-lasbeheer,
- Gemidelde warm-water-silinder-temperatuur en
- Die bepaling van besparings asook die verspreiding daarvan.

Die feit dat sommige partye geafronteer gaan voel as gevolg van nuwe warm-water-lasbeheer-paradigmas wat daargestel gaan word, is onontbeurbaar. Die residentiële kliënt het vir jare lank aan die korste ent getrek en dit is nou tyd dat iets aan die situasie gedoen moet word.

Sleutelwoorde: Warm-water-lasbeheer, warm-water-silinder-temperatuur, menslike gedrag, besparings verspreiding.

CHAPTER 1

CHAPTER 2

CHAPTER 3

CHAPTER 4

CHAPTER 5

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].

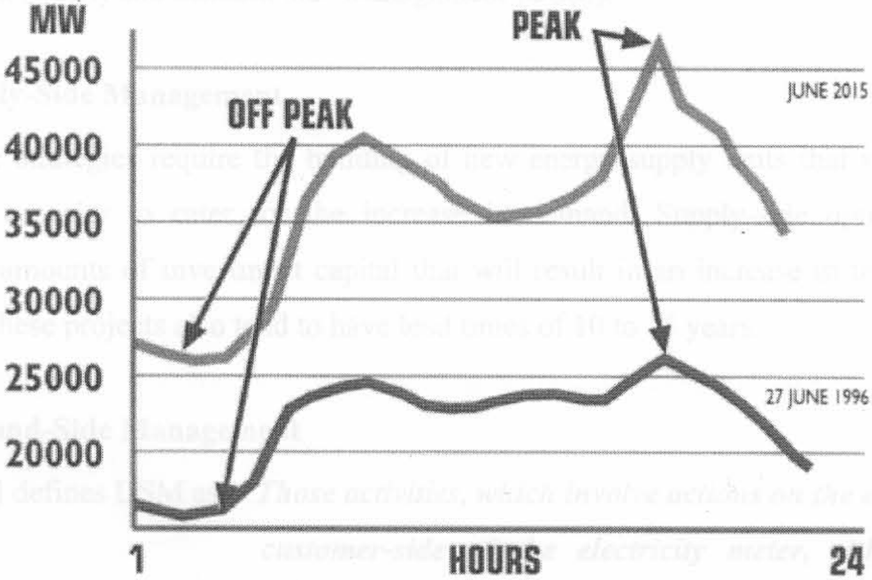


Figure 1.1: National demand profile - Actual values of 1996 compared with estimated simulation profiles for 2015 [1].

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

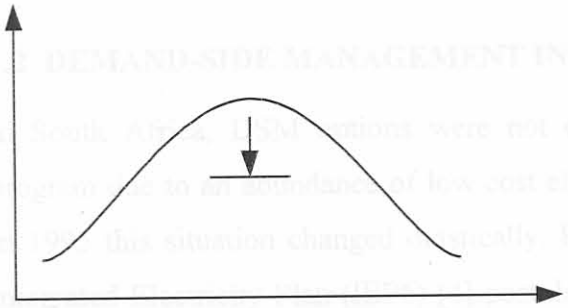
All around the world utilities must be pro-active in their supply strategies by predicting the future requirements of their existing consumers as well as new clients added to the network. A number of strategies can be implemented to match the supply with this increase in demand. These strategies can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

1.1.1 Supply-Side Management

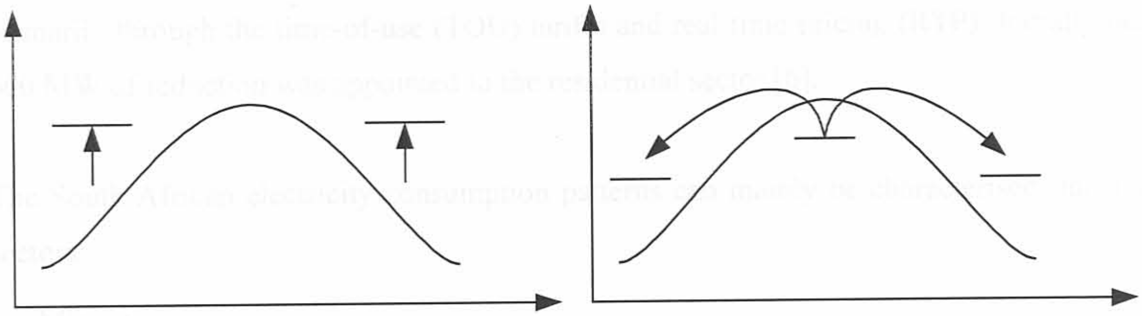
Supply-side strategies require the building of new energy supply units that will improve generating capacity to cater for the increase in demand. Supply-side options require substantial amounts of investment capital that will result in an increase in the electricity tariffs and these projects also tend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



Peak Clipping



Valley Filling **Load Shifting**

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].

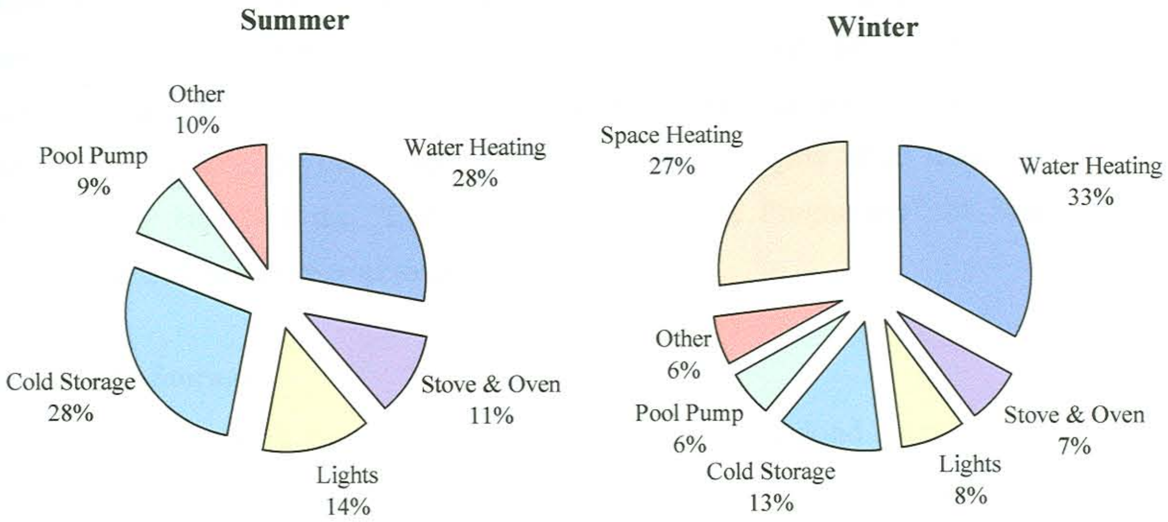
The South African electricity consumption patterns can mainly be characterised into four sectors:

- ☐ 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


Summer

Winter

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.

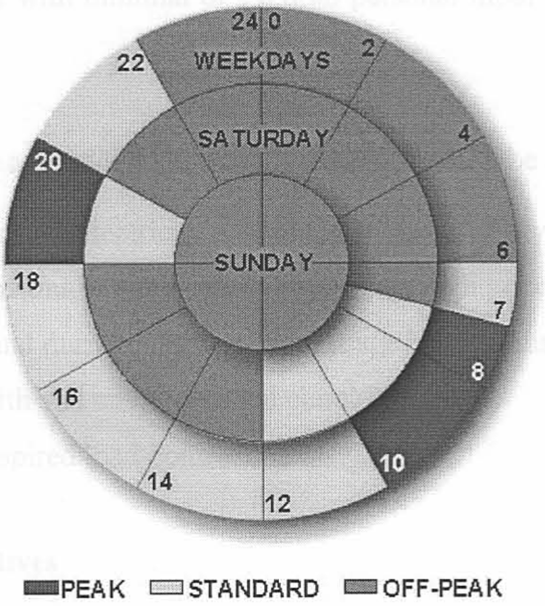


Figure 1.4: Megaflex time periods implemented during the calendar year of 2001 [14].

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.

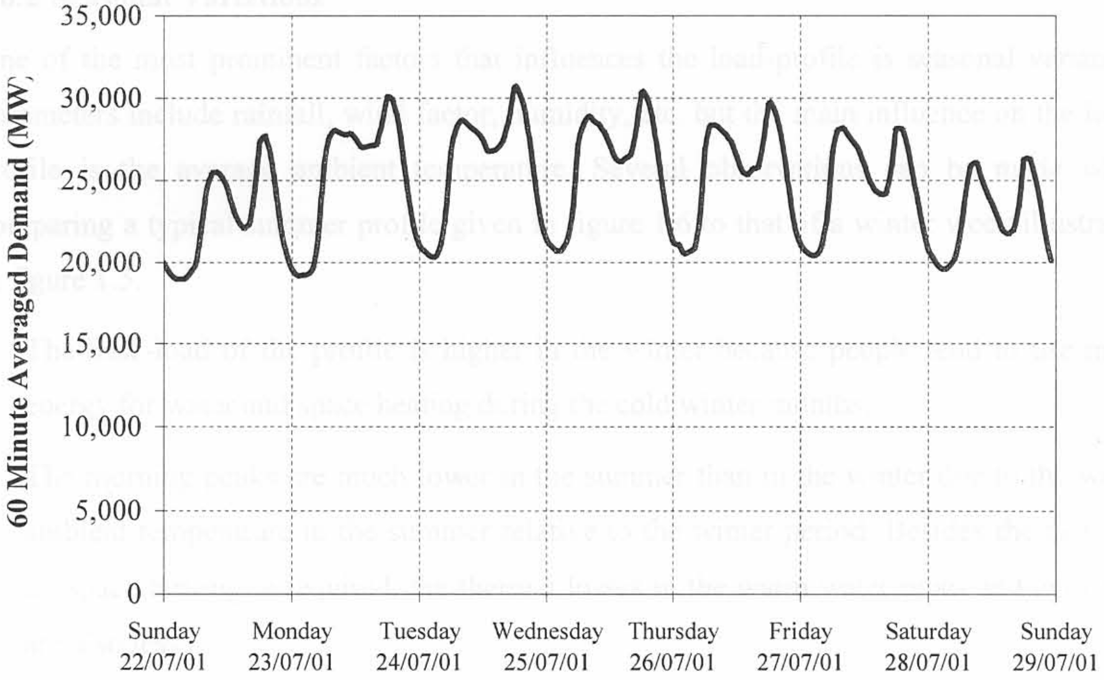


Figure 1.5: Eskom national load-profile for the week stating on Sunday, 22 July 2001.

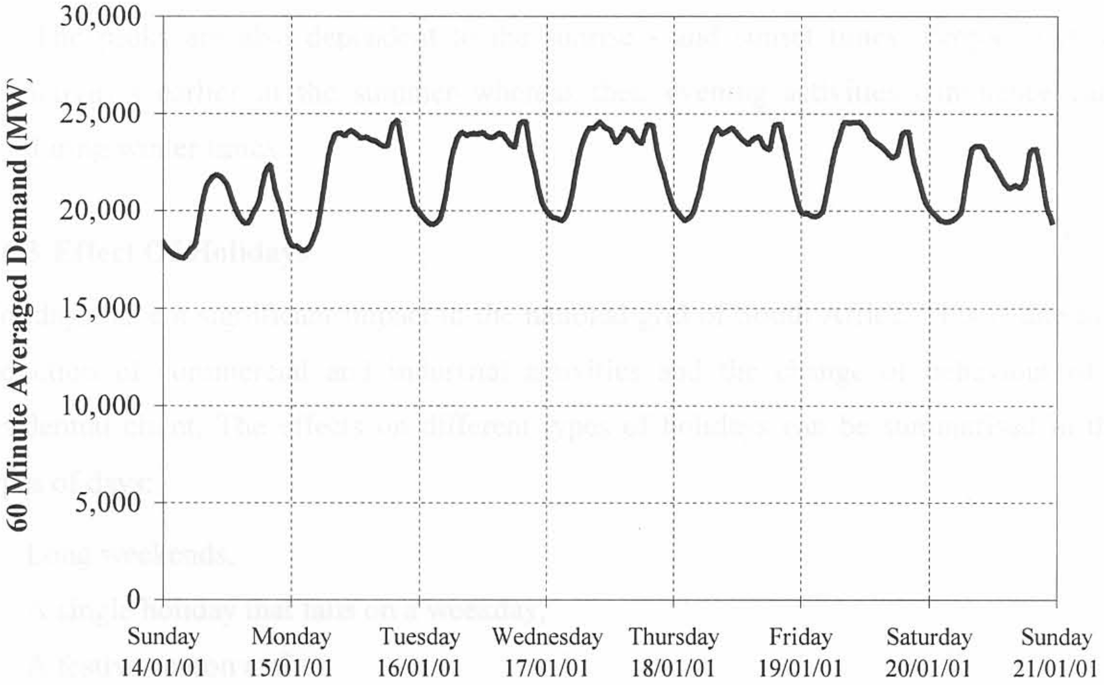


Figure 1.6: Eskom national load-profile for the week starting on Sunday, 14 January 2000.

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.

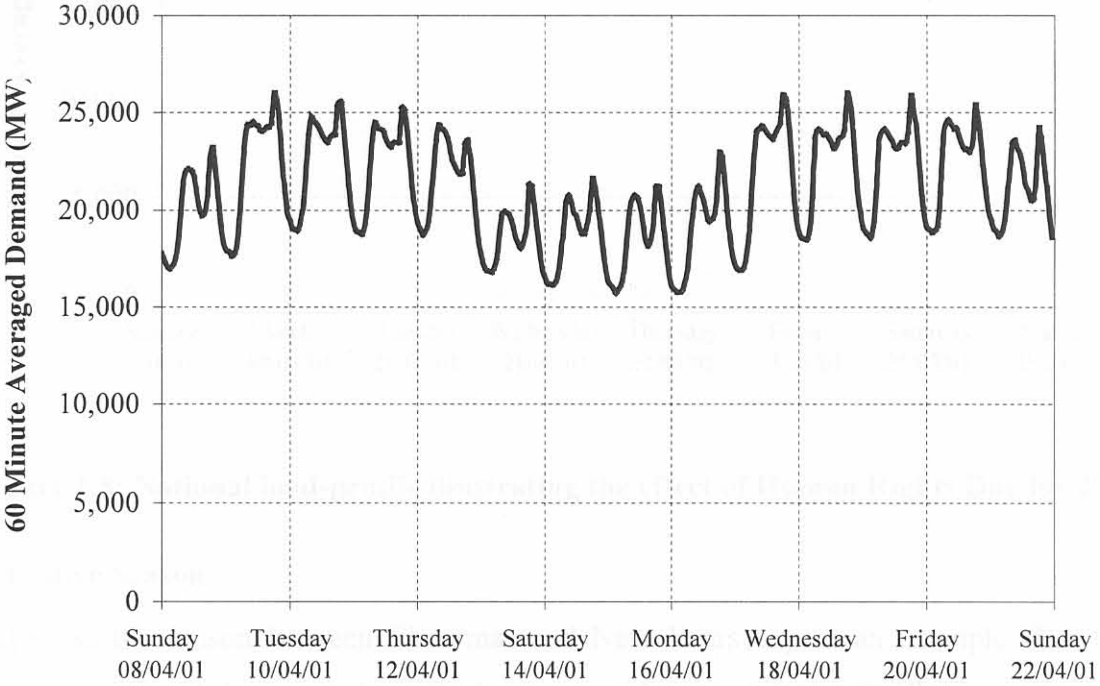


Figure 1.7: Two-week national load-profile for Easter weekend.

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.

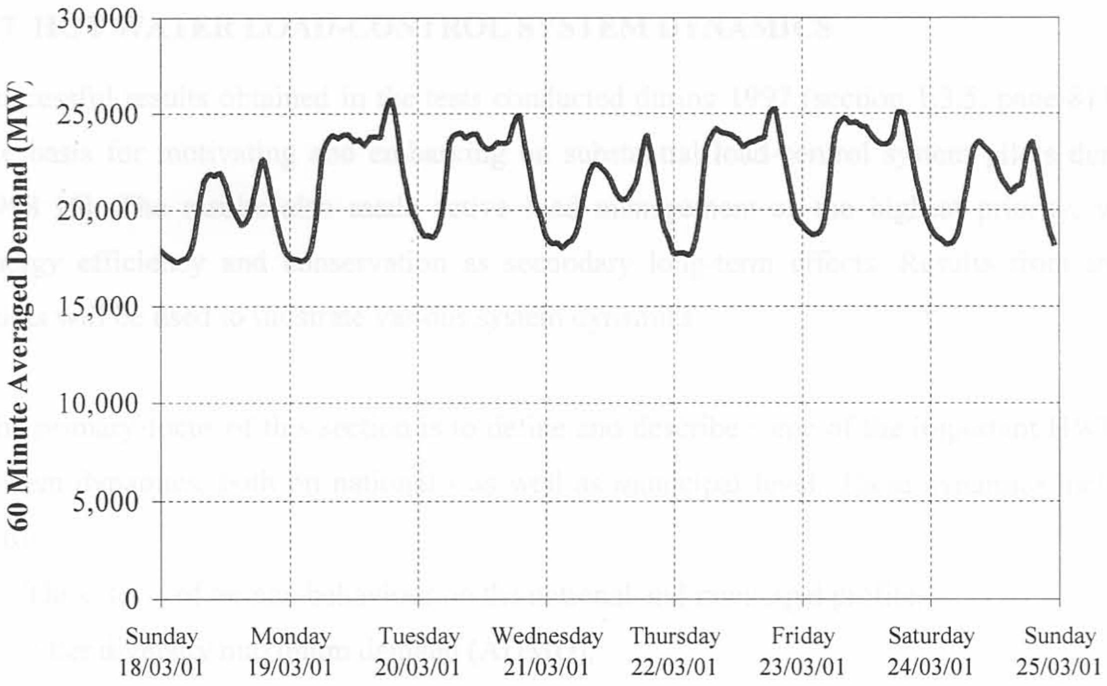


Figure 1.8: National load-profile illustrating the effect of Human Rights Day for 2001.

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).

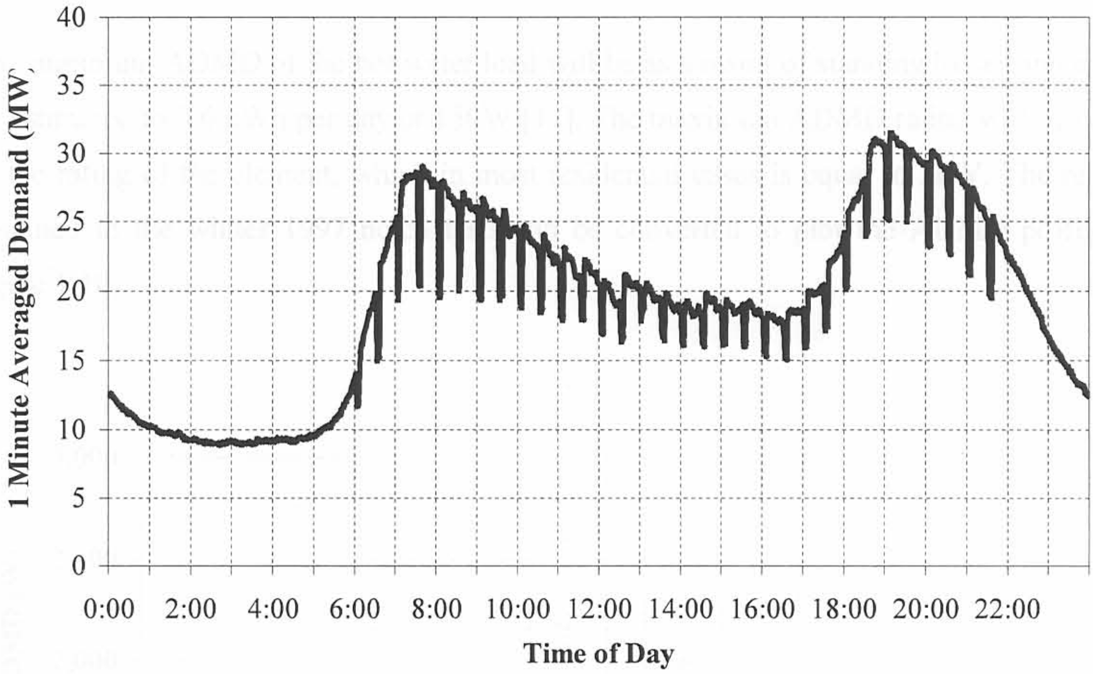


Figure 1.9: Example of notch test results.

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.

$$\text{TADMD} = \text{Total Load} - \text{Uncontrollable Load} \tag{1.1}$$

$$\text{ADMD} = \text{Total ADMD} / \text{Installed Relays} \tag{1.2}$$

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.

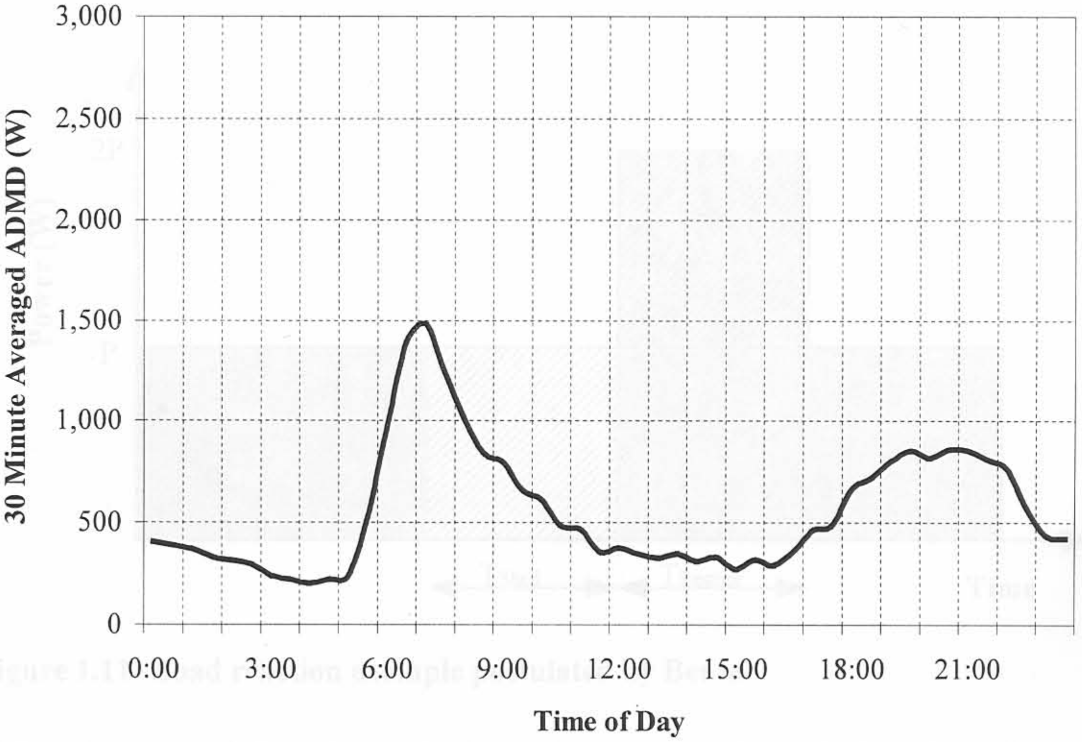


Figure 1.10: South African winter ADMD profile [13].

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.

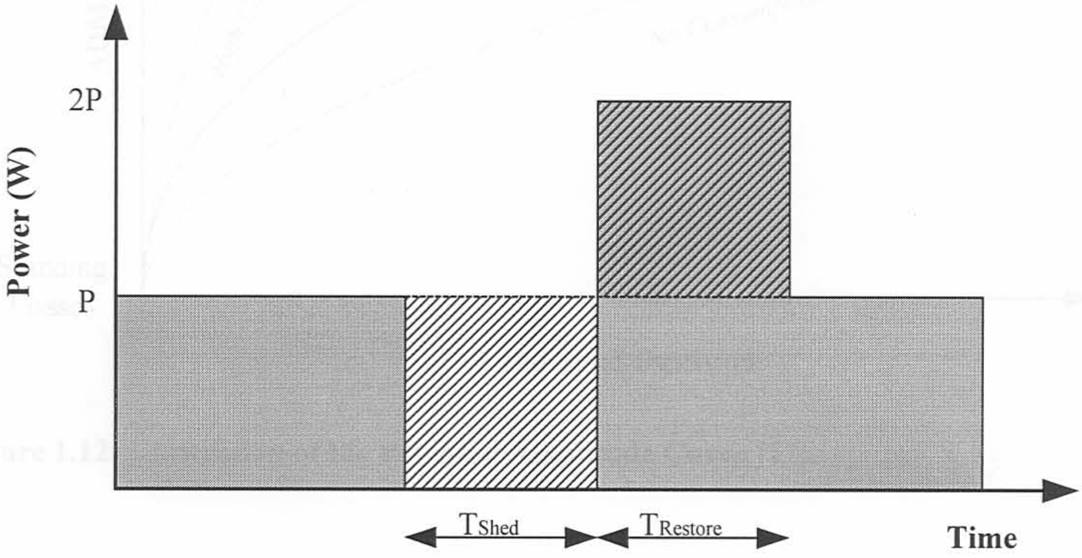


Figure 1.11: Load reaction example postulated by Beute.

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.

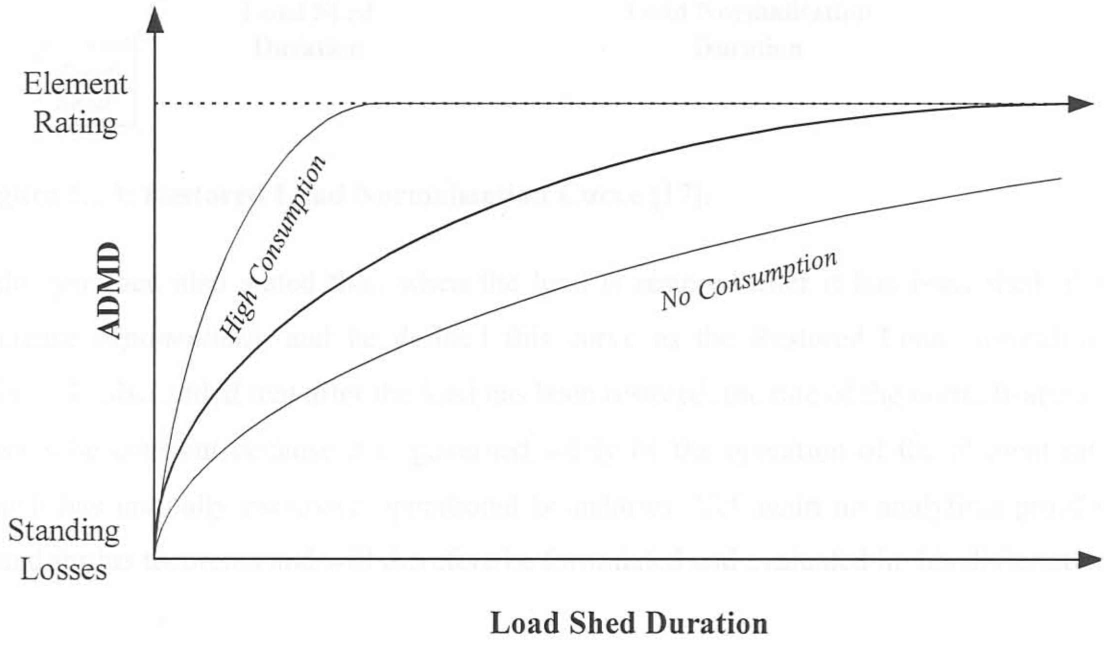


Figure 1.12: Illustration of the Potential Amplitude Curve [17].

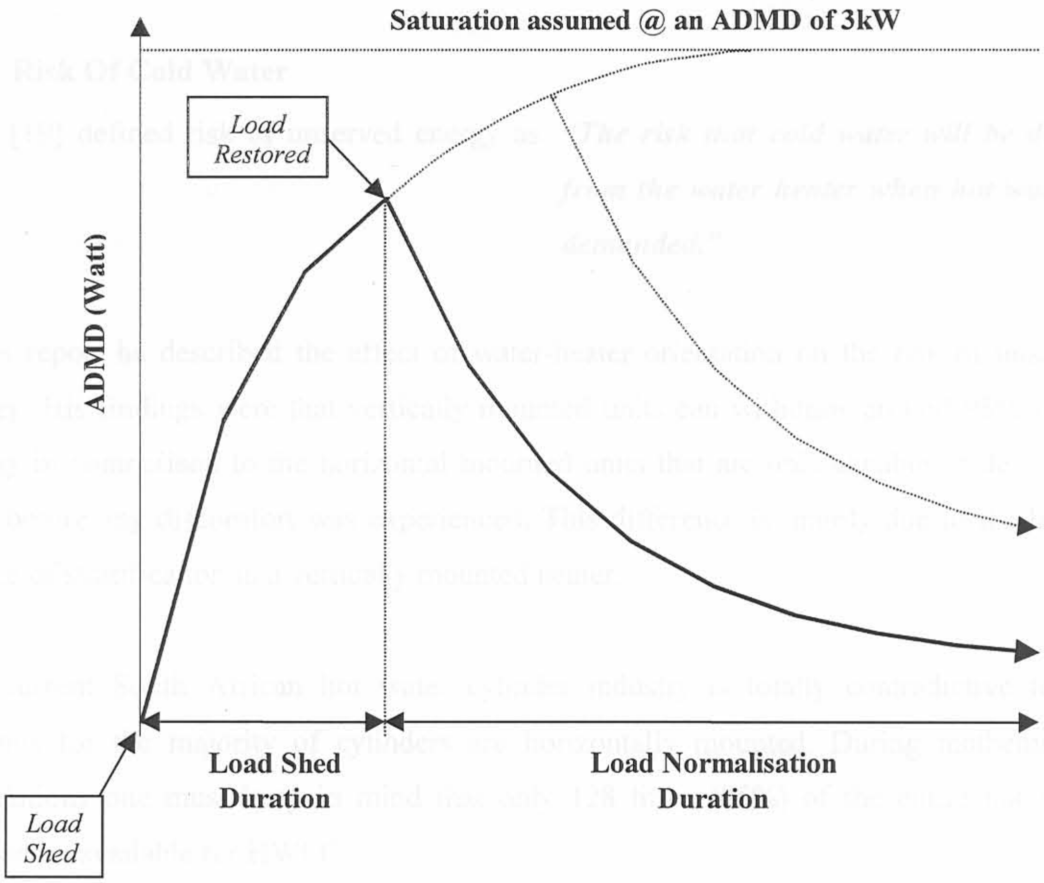


Figure 1.13: Restored Load Normalisation Curve [17].

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.

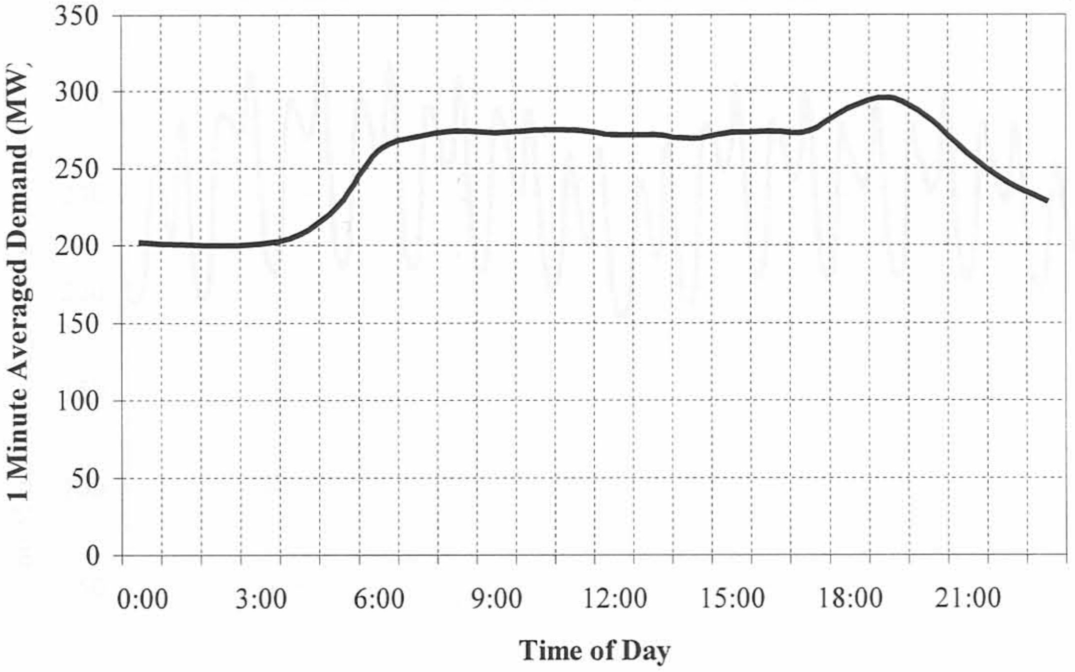


Figure 1.14: Winter load-profile only requiring control from 18:00 to 21:00.

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.

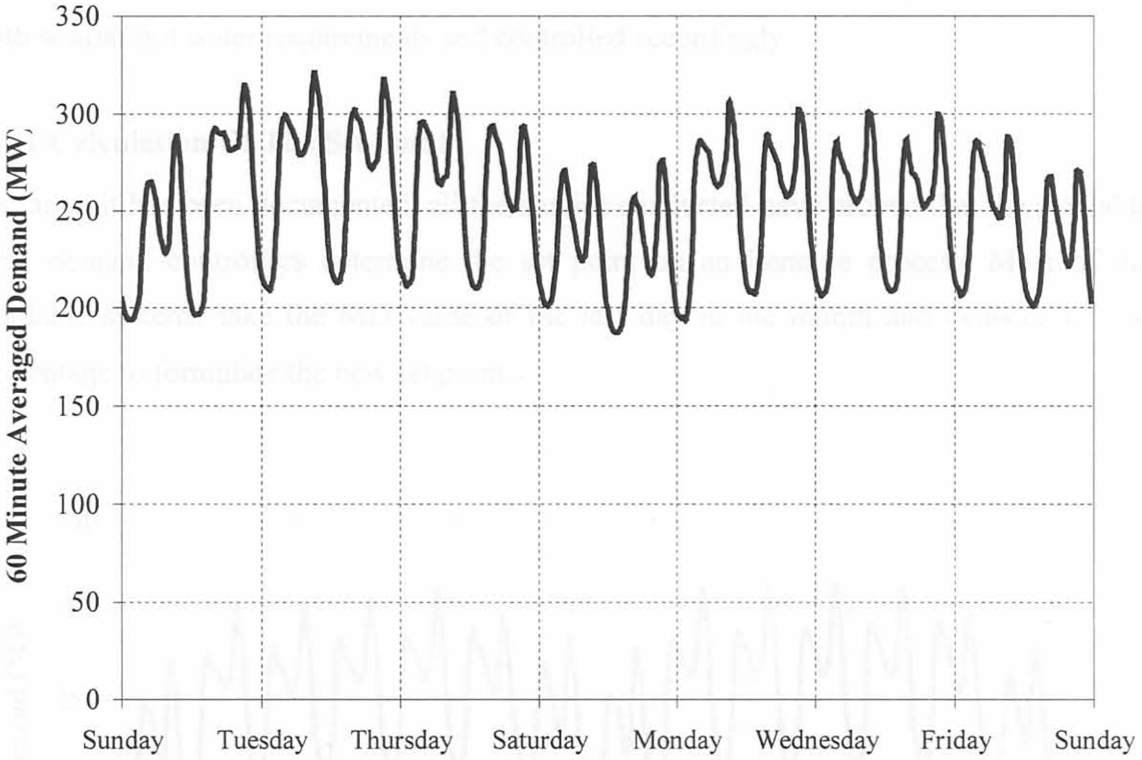


Figure 1.15: Load-profile requiring minimal MD control during the second week.

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.

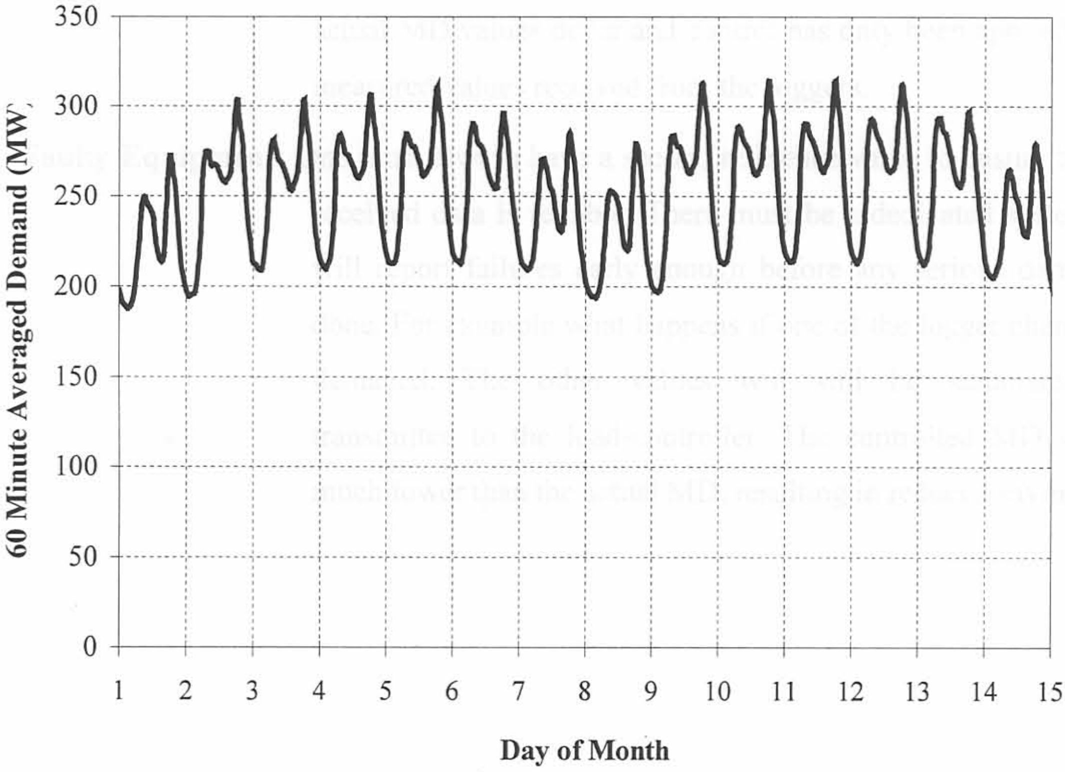


Figure 1.16: Load-profile for the first 2 weeks in June.

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.

CHAPTER 2

ENERGY POLICY AND MODEL DEVELOPMENT

Chapter 1 laid the basis for the current HWLC-situation in South Africa, wherein various problems and possible solutions were already identified. This chapter will use the information at hand to focus on the design of a HWLC-system from a consumer driven perspective, also satisfying the needs of the utility and municipality. The ideal HWLC-system would first be modulated holistically from a national perspective where after specific problem areas would be handled individually.

2.1 MODULATING HWLC FROM A NATIONAL PERSPECTIVE

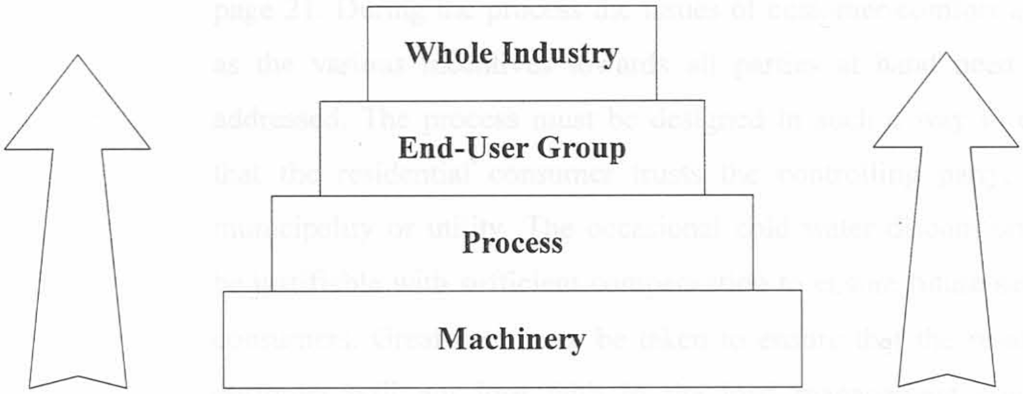


Figure 2.1: Illustration of energy-conversion models.

If one uses the energy conversion methodology (figure 2.1) developed by Delport [20], then load shifting from a supplier perspective would be postulated as follows:

- **Whole Industry:** This can be seen as the national load-profile. At the end of the day all DSM-efforts are initiated due to the peaky nature of the national profile. So, for the purpose of this study, all controllable hot water load will be seen as part of the whole industry
- **End-User Group:** This is the controllable load of each municipality. The aim of every municipal load-control system is to optimise the switching of hot water loads to ensure a minimum cost in terms of the tariff being used. The communication between the two levels is of great importance to link the energy shifted on municipal level with the national level. In this case the best option of communication would be to adapt the tariff in such a way to "force" the municipalities to shift their loads when the national peak occurs. The long-term option would be link all the HWLC-systems to a central controller, directly controlling the loads according to the supplier's needs.

- **Process:** This is the HWLC-algorithm for switching the hot water loads and also the monitoring of the system dynamics as described in section 1.7 on page 21. During the process the issues of customer-comfort as well as the various incentives towards all parties at hand need to be addressed. The process must be designed in such a way to ensure that the residential consumer trusts the controlling party, either municipality or utility. The occasional cold water discomfort must be justifiable with sufficient compensation to ensure future satisfied consumers. Great care must be taken to ensure that the residential customer will not lose faith in the load management controller resulting in the bypassing of the installed HWLC-unit.
- **Machinery:** This is the physical device. The limitations on switching must be known for each type of switch used; i.e. the amount of switching actions per minute, maximum current, the dead-time of the system, maximum definable groups, etc.

  Another important aspect regarding machinery is the ratings of the switchgear and transformers connected to the grid. If load is restored, what is the maximum dI/dt that the system can withstand without reducing the lifetime of any components. This also links up with the process: What is the predicted cold-load pickup and will it be more than the installed capacity of the region? The result of switching must not infringe on the life cycle of critical hardware. It will totally defy the purpose of DSM.

Thus, at the end of the day the primary objective remains optimal load shifting in terms of the national load. The whole process of energy shifting and the dynamics of these actions have to be taken into account to ensure optimal control. Now that the HWLC-perspective is fixed, the load-control process can be transformed into an end-user model.

2.1.1 End-User Model

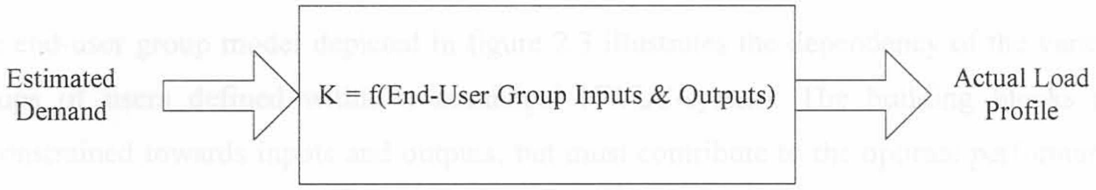


Figure 2.2: National load management modulation on a system level.

Figure 2.2 illustrates the HWLC-system from a global perspective with the estimated demand from which the possible peak period can be derived as main input. The system must react to the input values to minimise the load in a controlled fashion. The control is escalated down to the end-user group by manipulating the various local inputs to obtain the required global output as result of the summation of the local outputs. To understand the system, modelling must be done on a micro scale with the optimal system output as common goal. This micro scale model is known as an end-user model and requires the following inputs [20]:

- End-user Group Configuration,
- Electricity Tariff,
- Required Production Profile,
- System & Process Limitations and Constraints,
- Management Rules and
- Buffer Systems.

These inputs are then processed by the end-user group model delivering the following outputs [20]:

- Electricity Load-Profiles
- Buffer System-Levels

2.1.2 End-User Model Inputs

Input 1: End-user Group Configuration

The end-user group model depicted in figure 2.3 illustrates the dependency of the various groups of users defined within a municipal HWLC-system. The building blocks are unconstrained towards inputs and outputs, but must contribute to the optimal performance on national level rather than group level.

Residential consumers must be placed in groups with the same hot water requirements and behaviour. The system requires the TADMD of each group afterwards and can be obtained by means of channel separation tests. The TADMD is used as an accurate resemblance of the hot water energy consumption a selected the group at a specific time and type of day.

According to section 1.6.1 on page 16, the hot water load consumption patterns can be summarised into five categorical days:

- Monday and the day after a public holiday.
- Regular Tuesdays, Wednesdays and Thursdays.
- Friday and the day before a public holiday.
- Saturday.
- Sunday and public holidays.

In order to compensate for seasonal variations, TADMD-profiles of each user group must be extracted at least for every season but preferably for every month of the year.

Each TADMD-profile can also be seen as the amount of energy available for HWLC and is therefore defined as energy storage buffers. Each group has an energy buffer, as illustrated by the circles in figure 2.3, whereas the squire depicts HWLC-algorithms that must utilise these storage buffers according to certain constraints.

The HWLC-algorithms can either be used to curtail the stored energy during national peak hours or to manipulate the remaining energy in the storage buffer to control the MD during load restoration periods. During load restoration the cold-load pickup effect of one group can be minimised by shedding other groups with remaining storage capacity.

The temperature inside the hot water cylinder also lower bounds the capacity of each group. Customer-comfort-levels may not be infringed and therefore the available capacity must be adapted to ensure that the minimum cylinder temperature will never be less than stipulated by the residential consumer group agreement.

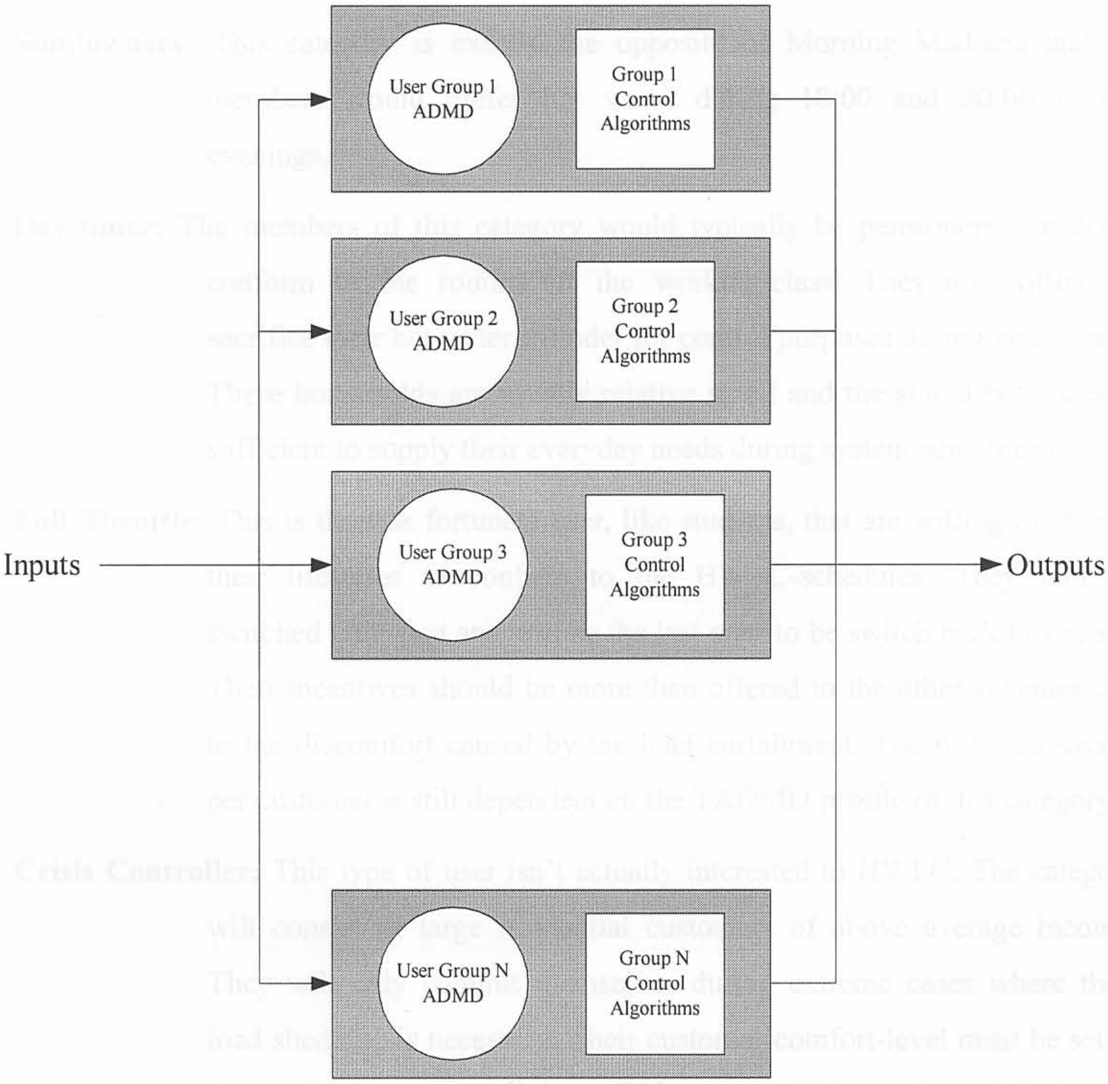


Figure 2.3: End-user group model for load-control from a national perspective.

For the purpose of this methodology, these five categories have been identified relating the main consumption patterns:

- ☐ **Morning Madness:** This is the type of person that would prefer to have hot water in the morning between 6:00 and 9:00. The primary objective of this category is to minimise cold-load pickup effects during the morning load restoration cycle and for load curtailment during the evening. These users may also be switched off during the morning peaks only if the load-controller is certain that the average cylinder temperature remains above the minimum allowable temperature between 6:00 and 9:00.
- ☐ **Sundowners:** This category is exactly the opposite of Morning Madness and its members would prefer hot water during 18:00 and 20:00 in the evenings.
- ☐ **Day-timer:** The members of this category would typically be pensioners that don't conform to the routine of the working-class. They are willing to sacrifice their hot water cylinder for control purposes during peak times. These households are usually relative small and the stored hot water is sufficient to supply their everyday needs during system peak times.
- ☐ **Full Throttle:** This is the less fortunate user, like students, that are willing to change their lifestyles to confirm to the HWLC-schedules. They will be switched OFF first and will be the last ones to be switch back ON again. Their incentives should be more than offered to the other schemes due to the discomfort caused by the load curtailment. The resultant saving per customer is still dependent on the TADMD-profile of this category.
- ☐ **Crisis Controller:** This type of user isn't actually interested in HWLC. The category will consist of large residential customers of above average income. They will only commit themselves during extreme cases where their load shedding is necessary. Their customer-comfort-level must be set to "ensure" hot water at all times. This group will be used to minimise the effect on the MD due to cold-load pickup after peak periods.

These categories can then be subdivided into three switching levels:

☐ Lenient,

☐ Regular or

☐ Frequent

depending on the occupant-versus-hot-water-cylinder ratio. A high ratio would result in a lenient switching level.

Input 2: Electricity Tariffs

The tariffs set forth by the supplier is the most important form of communication to depict the needs regarding the national load-profile. Municipalities must then react on the pricing signal to conform to optimal savings. Some municipalities might have different tariffs to specify the need of the supplier on a controlled basis.

An optimal choice for HWLC would be a TOU-tariff with a weekly schedule, changing monthly. The municipalities would easily accept this proposal because they have enough time to react to the change in tariff. A monthly MD charge must also be incorporated in the tariff to ensure that the peak isn't just shifted to another time of the day. The municipalities must be forced to control their cold-load pickup after the peak periods minimising its effect.

The municipality has a problem with the extreme diversity among the residential customers. The load management controller must be able to control the groups as if they were individual clients as illustrated in figure 2.3. Each group has it's own TADMD-profile and switching scheme that will control the group with customer-comfort as limiting parameter. If a client experiences problems with his current group setting, he can apply for a transfer to a regular or lenient switching level of the current group, or even to another group that might conform to the needs of his specific lifestyle. Each group will have its own tariff structure to ensure fair compensation for their contribution and particular form of discomfort.

Each time a group is selected for control, a database entry will be logged. With the TADMD of every group and the state of each switch known at any time of the day, the savings could be calculated in respect of the shifted energy. Any additional costs due to an increase in the MD as result of load shifting will be deducted from the total savings before it is distributed amongst the groups.

The load-controller must be intelligent enough to ensure that the cost of possible MD set point changes will be less than the savings due to the energy shifting during that time period. Take the Megaflex tariff as example:

$$\text{MD Cost} = \text{Energy Savings Cost}$$

$$(\text{MD Cost Per kW})(\text{Increased kW}) = (\text{Effective Cost Of Saving})(\text{Amount of kWh Shifted})$$

$$(\text{R}14.67/\text{kW})(1\text{kW}) = (35.4\text{c/kWh} - 14.85\text{c/kWh})(E)$$

$$E = \underrightarrow{71.39\text{ kWh}}$$

Thus with the Megaflex tariffs of 2001, the load management controller must be able to shift more than 71.39 kWh out of the peak time to justify an MD increase of 1kW.

Input 3: Required Production Profile

The required production profile is the requirements set forth by the utility, municipality and the end user as discussed throughout section 1.5 on page 10 .In general

- The utility requires a national load-profile with unity load factor,
- The municipality wishes to manipulate their local load-profile in order to minimise their utility bill while
- The end-user requires a HWLC-system that is “invincible” according to his preference lifestyle.

Input 4: System & Process Limitations And Constraints

The system limitations is defined by the HWLC-machinery, as described in section 2.1 on page 38. Each supplier of HWLC-hardware must also supply an ISO-OSI product specification document before installation to ensure that system time- and command constraints will be within the HWLC-application layer specifications.

All the process-limitations and constraints are mutual-inclusive with the end user group configuration and can therefore be omitted.

Input 5: Management Rules

Management rules depicts the governing body that protects all the parties involved. In other words, it is the set of rules that defines how the HWLC-system will be operated in terms of:

- ☐ Savings distribution,
- ☐ Risk of cold water,
- ☐ Customer-comfort-level infringement policy,
- ☐ Effects of human behaviour on the national and local load and
- ☐ Minimum allowable temperature of each user-group and - category.

The whole idea is to generate a win-win situation between the residential consumer, municipality and supplier by means of a predefined set of management rules.

2.1.3 End-User Model Outputs

Output 1: Buffer Systems and Buffer System Levels

The basis of HWLC is to manipulate the stored energy in the hot water cylinders (buffer system) according to the available energy. The TADMD of each user group is an indication of the available energy of that group at a certain time of the day and can be used to calculate the total amount of buffered energy available for HWLC-purposes.

The customer-comfort-levels directly influence the amount of extractable energy of each group and is therefore defined as the buffer system level. If the buffer system level is too low, then the risk of cold water will increase significantly.

Output 2: Electricity Load-Profiles

The load-profiles for each user group must be mutually inclusive to the contribution of lowering the peaks on national level. Optimal regulating of this profile requires that the dynamics of each HWLC-system must be understood and simulated in order to conform to the management rules.

One can apply the developed model on a new or even existing HWLC-system. Existing HWLC-systems does not particularly compensate for the effects of cold-load pickup beforehand and does not take customer-comfort into account. The main focus from here on will specifically be on the understanding and modulating these unresolved requirements.

2.2 TAKING A CLOSER LOOK AT COLD-LOAD PICKUP

What is this so called cold-load pickup (CLP) effect and why is everybody making such a fuss about it? The exact nature and dynamics of cold-load pickup are not yet defined and it is also the one effect that is capable of destroying the future of HWLC single-handedly.

During August 1999, Eskom conducted various experiments on a municipal HWLC-system with 9,000 installed devices. The objective of one of the experiments was to determine the savings-potential of HWLC as an energy shifting mechanism without any MD control. The results were catastrophic and without even looking in detail at figure 2.4 one can clearly see the problem at hand.

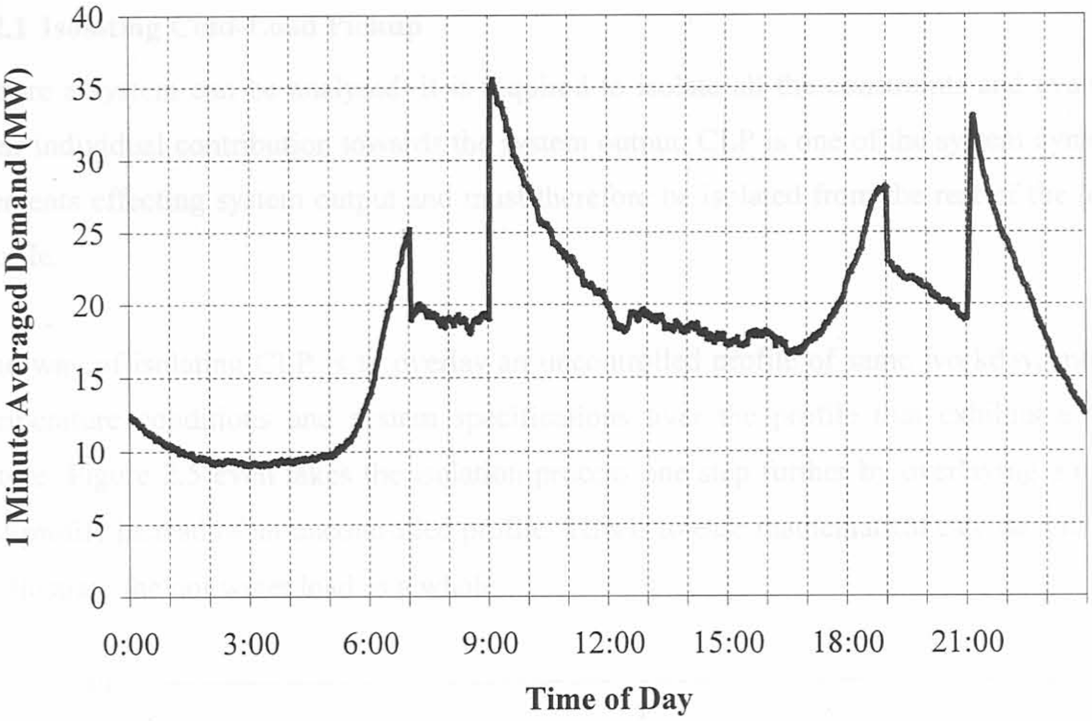


Figure 2.4: Energy shifting without MD control.

The initial examination of the load-profile can be very demoralising. A demand of only 6 MW was removed from the system during the morning peak period and when the load was restored an enormous increase in demand of 16 MW is noticeable. It appears as if the demand increased round about 3 times over the two-hour period. This increase is very common in the HWLC-circles and is known as cold-load pickup. In order to contain this phenomenon the only option would be to consider pro-active control.

Pro-active control requires that the load-controller is capable of predicting the outcome of CLP before any actions are taken. When CLP is mathematically defined, one can develop a HWLC-system that is capable of simulating the control actions the previous day and optimally schedule the control actions in advance. The first step in the mathematical process would be to isolate CLP from the total load-profile.

2.2.1 Isolating Cold-Load Pickup

Before a system can be analysed, it is required to isolate all the constraints and evaluate their individual contribution towards the system output. CLP is one of the system dynamic elements effecting system output and must therefore be isolated from the rest of the load-profile.

One way of isolating CLP is to overlay an uncontrolled profile of same weekday, month, temperature conditions and system specifications over the profile that exhibits a CLP nature. Figure 2.5 even takes the isolation process one step further by overlaying a notch test profile instead of an uncontrolled profile. This is to ease mathematical calculations and to illustrate the hot water load as a whole.

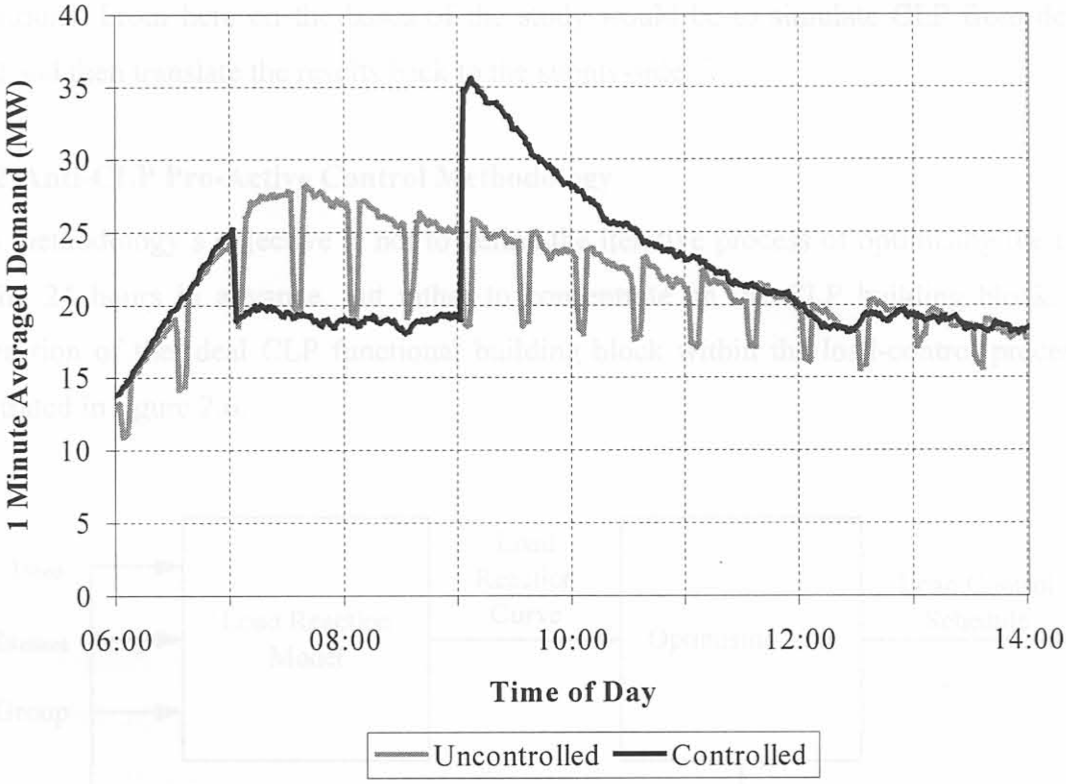


Figure 2.5: Uncontrolled and controlled load-profile overlay.

The overlay process suddenly enlightened two important facts:

- The increase in the MD is only 8 MW and not 16 MW as initially noticed because an uncontrolled load would have caused an MD of 28 MW on that specific day.
- The total load-profile consists of the base-load, regular consumption for the day and the increase in demand caused by CLP. Therefore

$$\textit{Total Load} = \textit{Base-Load} + \textit{Real-time HWL Consumption} + \textit{CLP} \qquad (2.1)$$

The research done from the days of Beute to modern day Calmayer all have one thing in common. That is, all the experiments regarding the dynamics of CLP during load-control were monitored from the supply-side and not on individual hot water cylinder level. With the technology available at that time their work was outstanding but not entirely true for all conditions. From here on the bases of the study would be to simulate CLP from device level and then translate the results back to the supply-side.

2.2.2 Anti-CLP Pro-Active Control Methodology

This methodology's objective is not to define the iterative process of optimising the load-profile 24 hours in advance, but rather to concentrate on the CLP building block. The interaction of the ideal CLP functional building block within the load-control process is illustrated in figure 2.6.

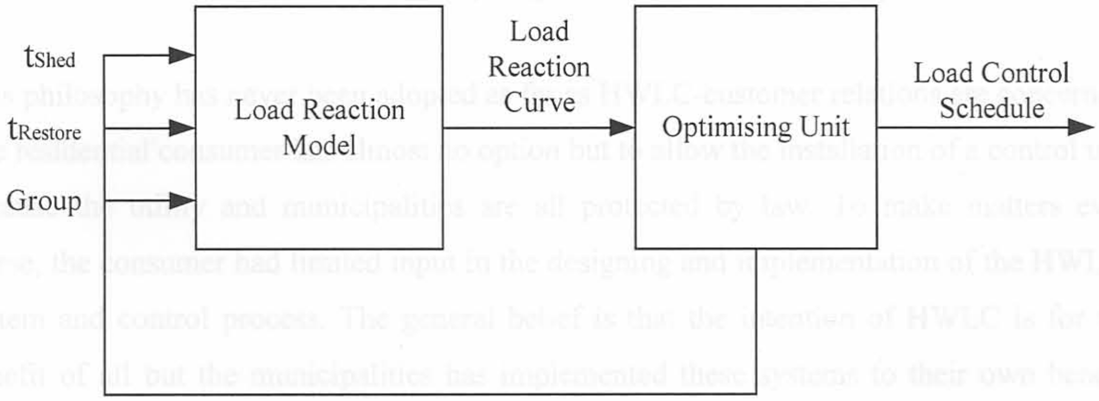


Figure 2.6: Interaction between the Load Reaction model and the Optimising unit.

During each iteration of the optimising process, the load-profile-optimising module passes three input variables to the CLP calculation module:

- ☐ The selected HWLC-group for the current iteration.
- ☐ The time of the day that the group must be switched off (t_{Shed}).
- ☐ The time of the day that the supply of the group must be restored ($t_{Restore}$).

These inputs are then used in a mathematical data manipulation process (section 3.1, page 63) on the system constraints of the selected group. The optimising module must repeat this process for all the user groups selected for control. The results obtained for each group must then be summated in order to construct the predicted national load-profile. The optimising unit must verify that all the system requirements set forth by utility, municipality and residential consumer were met, or else repeat the iteration again before it publishes the load-control schedule.

Finally the demand specifications are met, but the residential customer remains at the bottom of the food chain. Something has to be done about this occurrence and therefore is the next section committed to the integration of the residential consumer's needs into the HWLC-system.

2.3 RESIDENTIAL CONSUMER ORIENTATED CONTROL

"The customer is always right, even when he is wrong."

This philosophy has never been adopted as far as HWLC-customer relations are concerned. The residential consumer has almost no option but to allow the installation of a control unit because the utility and municipalities are all protected by law. To make matters even worse, the consumer had limited input in the designing and implementation of the HWLC-system and control process. The general belief is that the intention of HWLC is for the benefit of all but the municipalities has implemented these systems to their own benefit without taking the needs of the consumer into account. Obviously something went wrong and the aim from here on would be at least to start the process of consumer-orientated control.

Three basic residential consumer needs have been identified throughout chapter 1:

- ☐ Consumers must have a say when they would prefer to have hot water,
- ☐ A minimum hot water temperature level should be agreed upon and formulated in the management rules and
- ☐ Incentives should be paid out to compensate for any inconvenience caused.

The first step towards residential consumer orientated control would be to address these three basic needs. Loyds [9] clearly stated in section 1.6 that the influence of any DSM option should be known before implementation and therefore should methodologies for each of these needs be formulated. The first need to be addressed is the preference group configuration and its effect on an HWLC-system.

2.3.1 Consumer Group Configuration

The motivation behind consumer group configuration is to give the residential consumer an option to choose between various control strategies. Residential consumers are currently randomly assigned to control groups in order distribute the hot water load evenly over all the groups. This solution is undoubtedly not optimal due to the diversity among user consumption.

Some users would be willing to give their entire hot water energy load for control purposes as long as they are guaranteed of hot water for a specific timeframe, i.e. between six and seven in the morning. The implication is that this type of consumer would not mind at all if the water temperature is below 40°C during the evening peak. The advantage is thus that this agreement entitles the load-controller to extract another 15°C of energy that would previously have been impossible since the client would have been listed as a risk of cold water.

Another motivation is when consumers have more than one cylinder installed on their premises. It is customary that one cylinder is dedicated to service the main bedroom area whereas the other one is used for washing and cleaning purposes. It is eminent that expectations on the two cylinders would be different and therefore is it possible that intelligent group categorisation lead to a more efficient and customer-orientated system.

A good place to start the user pattern classification process is to gather all relevant information about the actual needs of the consumer. The data must then be processed in order to identify groups with similar behavioural patterns.

A simple questionnaire can be handed out during installation and might include the following questions:

- ☐ What is the unique device address of each one of the HWLC-devices installed?
- ☐ What is your electricity account number?
- ☐ How many people occupy the dwelling?
- ☐ Do they shower or bath and at what time of the day?
- ☐ How many people are at home during daytime?
- ☐ Specify the rating (E.g. 3kW) as well as orientation (horizontal or vertical) of every hot water cylinder installed.
- ☐ What is the temperature setting of each cylinder?
- ☐ Do you switch one or more cylinders off at any time of the year; if so when and for how long?
- ☐ At what time of the year do you prefer to go on holiday and for how long?

From the data gathered, a consumer can be classified into any one of the categories defined in section 2.1.2. A consumer can only migrate from one category to another if substantial motivation was presented but control level selection (lenient, regular, frequent) can be changed easily. The consumer data is finally ready for storage in a consumer database which must at least include the following fields:

- ☐ Unique HWLC-device address,
- ☐ Rating of the installed cylinder
- ☐ Personal details such as initials, surname, physical address, phone number, electricity account number, etc and
- ☐ The selected control category and group number.

Once the categorisation process is finished, the control strategy can be evaluated on group level - opening the door for detailed system behavioural data extraction. It is possible to extract data for every day of the year, but that would be a very costly process and therefore should one study section 1.6 (page 15) again to identify the minimum data fields required to compensate for human behaviour. The data should compensate for:

- Weekly patterns in human behaviour,
- Seasonal variations and
- Various holidays.

In terms of the study made in chapter 1, weekly patterns can best be described by extracting only four types of days:

- **Monday**: People tend be reluctant to get out of bed and go to work.
- **Wednesday**: It is an accurate estimation for Tuesday – Thursday.
- **Friday**: The customarily social night of the week exhibits unique characteristics.
- **Sunday**: Saturday and Sunday could be treated separately but it would be a fair estimation to treat these days similarly.

To compensate for the seasonal variation, a set of weekly patterns should at least exists for every season but preferably for every month, depending on the size of the HWLC-system. A fair representation of customer behaviour consists of 48 (4 days per month x 12 months) profiles per group that has to be stored in the database.

Each holiday should be treated on merit. The management rules must clearly specify which type of day should be used in order to estimate the consumption pattern for that specific holiday. Let's take an example where the public holiday falls on a Wednesday. In the first place the controller should know from the management rules that it is a public holiday. In second place should the controller apply the set of management rules to determine that the holiday must be treated in the same fashion as if it was a Sunday.

At this stage the nature of the stored data is known, but no actual data has been recorded. The data for a specific type of day is stored in the form of a percentage consumption profile, illustrated in figure 2.7, and is obtained by means of a channel separation test.

A channel separation test requires that only one group is notched at a time and the resultant notch is visible on the total load-profile, which is equal to the TADMD of that group. This TADMD is then divided by the installed capacity and the result is used to plot a percentage profile for the group.

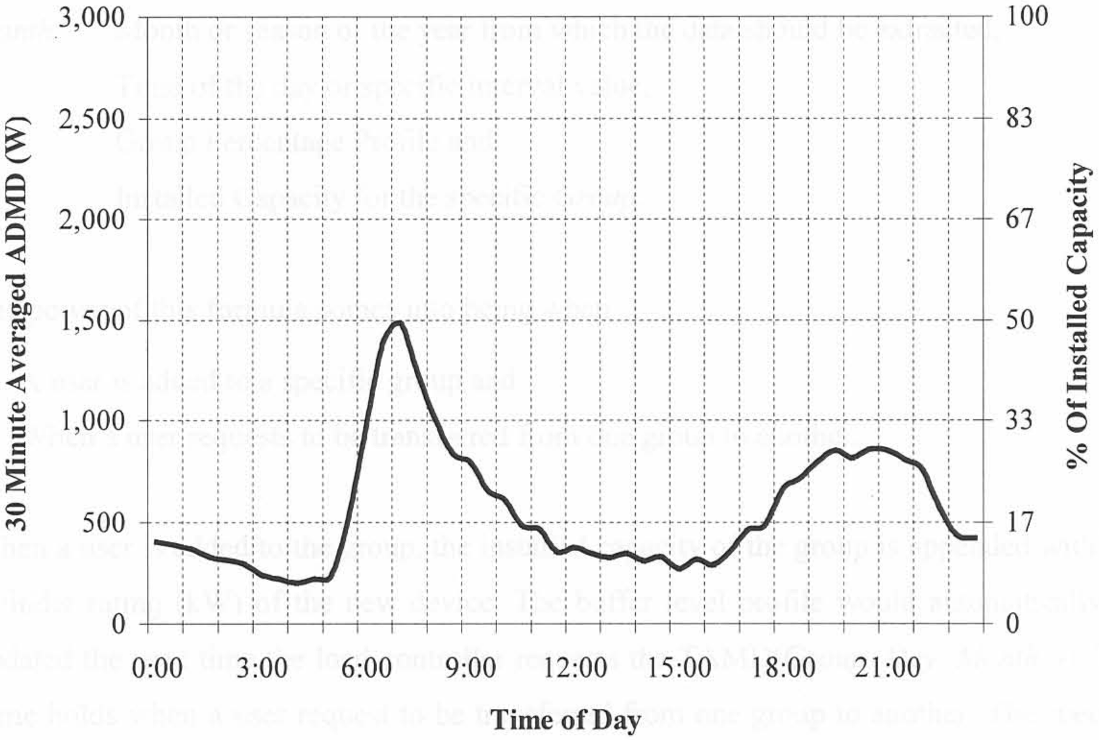


Figure 2.7: Percentage profile of the South African hot water consumption.

The advantage of using a percentage profile is that the profile is independent of the amount of devices in the group. The controllable amount of energy available in the storage buffer of each group can be obtained by

$$\mathrm{TAMD}(\mathit{Group}, \mathit{Day}, \mathit{Month}, t) = \mathrm{GPP}(\mathit{Group}, \mathit{Day}, \mathit{Month}, t) \times \mathrm{IC}(\mathit{Group}) \tag{2.2}$$

where,

Group	Specific group or category number,
Day	Selected day pattern,
Month	Month or season of the year from which the data should be extracted,
t	Time of the day or specific interval value,
GPP	Group Percentage Profile and
IC	Installed Capacity for the specific *Group*.

The power of this formula comes into being when

- A user is added to a specific group and
- When a user requests to be transferred from one group to another.

When a user is added to the group, the installed capacity of the group is appended with the cylinder rating (kW) of the new device. The buffer level profile would automatically be updated the next time the load-controller requests the TAMD(*Group, Day, Month, t*). The same holds when a user request to be transferred from one group to another. The specific user's installed capacity is subtracted from the old group and then added to the new group's installed capacity without interfering with the actual profile data.

Now that the process of user classification is defined, the next step would be to minimise risk of cold water. From there on one would be able to derive a process from which the average hot water cylinder temperature of each group can be determined.

2.3.2 Minimising Risk Of Cold Water

HWLC is a concept that is not all too familiar to the general public. This has numerously led to great misunderstandings, as the consumer will not hesitate to bypass the residentially installed control unit the minute that his hot water supply is insufficient, even if it wasn't as result of any load-control actions taken.

After a number of units have been bypassed, the control system is forced to shed the remaining operational devices for a longer time in order to maintain previous saving levels. This in turn causes a snowball effect because more HWLC-units are being bypassed and the honest users must endure cold water at an escalating rate. Consequences like these can be avoided by installing a more customer orientated system with a high switchable device resolution. On the consumer side the community has to be educated regarding the local and global advantages of HWLC.

Another aspect of concern is the household size versus the cylinder capacity ratio. A higher ratio indicates a greater risk of cold water. This problem can be overcome by increasing the temperature setting on the thermostat of the hot water cylinder. Care must be taken to ensure that the additional energy consumed due to the change in temperature setting during regular usage isn't more than the saving contributed by load-control actions.

2.3.3 Average Cylinder Temperature Model

The problem at hand is that the management rules require that a consumer must be guaranteed of a minimum cylinder temperature during specific timeslots of the day. The ideal solution would be to constantly measure the temperature of every individual hot water cylinder in the field and to control the cylinder temperature accordingly. With the available technology in mind this option tends to be as an Utopian dream and therefore the search must continue for a plausible solution.

Delport, Jooste and van Harmelen [21] postulated that a group of cylinders can be defined as a single cylinder with equal capacity and consumption of the summated capacity and consumption of the individual cylinders. E.g. A group consisting of ten 150 litre (3kW) hot water cylinders can be estimated as a single 1500 litre cylinder with an adjustable consumption rating of 0 – 30 kW. The TADMD-profile of the group can therefore be used as the consumption and losses pattern of a single 1,500 litre cylinder.

The temperature prediction model requires the following inputs:

- Installed capacity of the group,
- Effective water capacity of the group,
- Uncontrolled TADMD of the group and
- The expected shedding (t_{Shed}) and restoration times ($t_{Restore}$).

The model then interprets these inputs in conjunction with a mathematical iteration process to plot an estimated cylinder temperature curve for the specific group. This mathematical process is described in detail in section 3.2 on page 87.

Both the load-controller and the load-optimising module can use the temperature prediction model to determine the average cylinder temperature of the group. Management rules force the optimising module to reschedule a group when the predicted temperature for a timeslot is below its specified temperature threshold level. The temperature threshold level of a group doesn't have to be the same value throughout the day, but the average cylinder temperature within a specific timeslot is not allowed to go below its specified level.

2.3.4 Calculation And Distribution Of Savings

This is exactly where HWLC gets a bit hairy. The municipality is fighting for the savings in order to pay for the installed hardware, whereas the residential consumer feels that he is entitled to a part of the savings due to discomfort caused by the system. Both parties have a valid argument but a win-win solution has to be presented to ensure the future of HWLC.

To solve the problem at hand, one should go back to the various objectives of the utility, municipality and residential consumer in chapter 1. In summary the aspects of concern would be to define an optimal cost-output-function for the entire HWLC-system to:

- ☐ Minimise generating costs on the utility level,
- ☐ Minimise the utility bill on a municipal level and to
- ☐ Ensure compensation for customer discomfort caused.

Savings On Utility Level

The only way a utility can save money in terms of HWLC is to utilise its generation infrastructure optimally. The tariff structure set forth to the municipality must reflect the areas where control is required, i.e. where the system isn't optimally utilised. A TOU-tariff structure would benefit both utility and municipality and in this case Megaflex in particular lends itself more towards being the "optimal" tariff structure. RTP is at the moment too risky due to the municipality's high base-load and low controllable hot water load at certain times of the day. RTP in itself would not motivate optimal HWLC-actions due to the possibility small of savings.

Currently, Megaflex's peak times also co-inside with the prominent residential peaks of the municipal load-profile. Thus, as far as the utility is concerned, optimal control would be to shift energy out of the national peak times into the off-peak times instead of the conventional peak clipping methodology. This strategy then satisfies the utility's needs and a fixed baseline is set on which the rest of the model can be developed.

Savings On Municipal Level

The total cost of a HWLC-system consists of two parts:

- ☐ **Fixed Costs**: This is the initial capital required to install the HWLC-system. Usually investors would finance these projects if the payback period is less than 3 years.
- ☐ **Operating Costs**: This includes maintenance contracts, customer care and operational personnel, consumer educational projects and any other expenses directly related to HWLC.

The operating costs are not that much, usually estimated between 10 and 20 percent of the capital cost, and can easily be covered by the MD-reduction-savings. Savings related to energy shifting actions must therefore be distributed to pay the fixed costs and to compensate the residential consumer. The actual distribution percentage will vary from installation to installation, depending on the minimum monthly down payment towards capital costs. The distribution percentage towards the consumer must increase substantially after the final capital costs down payment has been made.

Savings Distribution On Consumer Level

"Money is the root of all evil."

The main objective is to ensure that the situation doesn't change from bad to worse. The assumption is that no incentives are currently being paid out directly to the residential consumer. The next stage in the compensation process should be to distribute savings in a fair and auditable fashion between consumers. One can easily cause a riot within the residential community when certain groups receive more benefits than what their contribution were to the total savings effort. The tariff structure, in collaboration with the management rules, should also prevent unnecessary migration of consumers between groups. A large migration effort could disrupt the shape and characteristics of the TADMD profiles where after channel separation tests have to be conducted again.

"One hand washes the other"

This philosophy also holds for the selected HWLC-strategy of this dissertation. During the morning peak period between 7:00 and 10:00 most of the groups, except Morning Madness would be switched off. These groups will be restored at 10:00 where the reserves in Morning Madness will be used to minimise the cold-load pickup in terms of MD control. Morning Madness does not contribute directly to the savings, but is indeed very important during load restoration and therefore can cross-subsidisation not be avoided.

The TADMD-profile of a specific group is a representation of its amount of energy available for HWLC at any specific time of the day. From another perspective the TADMD is an indication of the amount of energy that a specific group contributed towards the HWLC-effort and can therefore be used as an indicator during the savings calculation.

The marginal saving per kWh can be obtained by:

$$p.u.Savings = \frac{TotalEnergySavings}{\sum_{n=1}^{Days}\sum_{m=1}^{Groups} SGC(n,m)}$$

where,

$p.u.Savings$	The marginal saving of one kWh (R/ kWh)
$TotalEnergySavings$	The total energy shifting saving for the billing period (R)
$SGC(n,m)$	Specific Group Contribution of the mth group for the nth day of the current billing month (R)
$Days$	The amount of days in the savings period i.e. Days in the billing month and
$Groups$	The amount of HWLC-groups.

The marginal saving can now be applied to each user group from which the contribution per member can be calculated. Savings can either be paid out in the form of a reduced electricity bill or directly cash in hand. Although the latter option seems frivolous, it is more of a psychological effect because the residential consumer will physically "see" the benefits of HWLC in monitory value.

2.4 CONCLUSION

Finally al three entities within the HWLC-process are mutually satisfied which concludes the methodology development process. As noted throughout this chapter, various mathematical derivations will be discussed in detail in chapter 3. The methodology might be altered some day, but for now it can be seen as a step in the right direction.

CHAPTER 3

MATHEMATICAL MODEL DEVELOPMENT

In this chapter the complex mathematical requirements of the load reaction model and the average cylinder temperature model will be discussed in detail. At present the need exists in the market to implement these two models into the existing HWLC-systems, but it must be used to open the doors for future possibilities.

It has been found in section 1.7.3 that the mathematical relations on load reaction are still inconclusive. In this chapter the possibility to predict the effects of load-control actions would be viewed from device level, instead of the traditional system level.

Customer-comfort-levels for each user group are specified in the management rules in terms of a minimum allowable cylinder temperature. With open loop control as the predominant communication topology, it is impossible to measure each individual cylinder's temperature. The only remaining possibility is to predict the average cylinder temperature for each group before or during control actions. Existing prediction models will be adopted to ensure integration into existing HWLC-systems.

Case studies will also be done on actual municipal data to validate the integration of the two models when applied within existing HWLC-systems.

3.1 LOAD REACTION MODEL

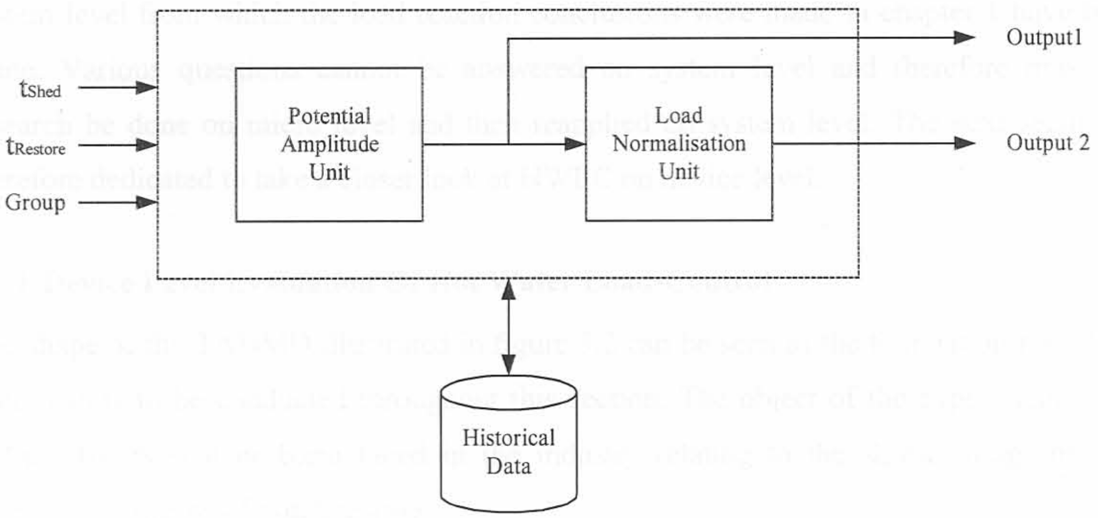


Figure 3.1: Composite layout of the Load Reaction Model.

The load reaction model was designed to predict the effect of a HWLC-action on the municipal and national load-profile. Two effects were noticed in chapter 1 when the hot water load was restored. The one is the increased load at the time of restoration (Potential Amplitude Curve) and afterwards the normalisation of the load (Load Normalisation Curve) occurred as secondary effect.

Figure 3.1 is a composite illustration of the load reaction model introduced in section 2.2.2 on page 50. The model itself comprises of two components namely:

- The Potential Amplitude Unit and
- The Load Normalisation Unit.

Both these units are required when predicting the effect of HWLC-actions, but it is possible to develop each unit separately according to the global system specifications and integrate it back into the model.

One HWLC-system is capable of controlling up to 16 million devices, but the average installation is in the order of 10,000 to 15,000 units. Data evaluation is usually done on system level from which the load reaction conclusions were made in chapter 1 have been made. Various questions cannot be answered on system level and therefore must the research be done on micro level and then reapplied on system level. The next section is therefore dedicated to take a closer look at HWLC on device level.

3.1.1 Device Level Evaluation Of Hot Water Load-Control

The shape of the TADMD illustrated in figure 3.2 can be seen as the foundation for all the experiments to be conducted throughout this section. The object of the experiments is to address the typical problem faced in the industry relating to the shortcomings of data extracted by means of notch testing.

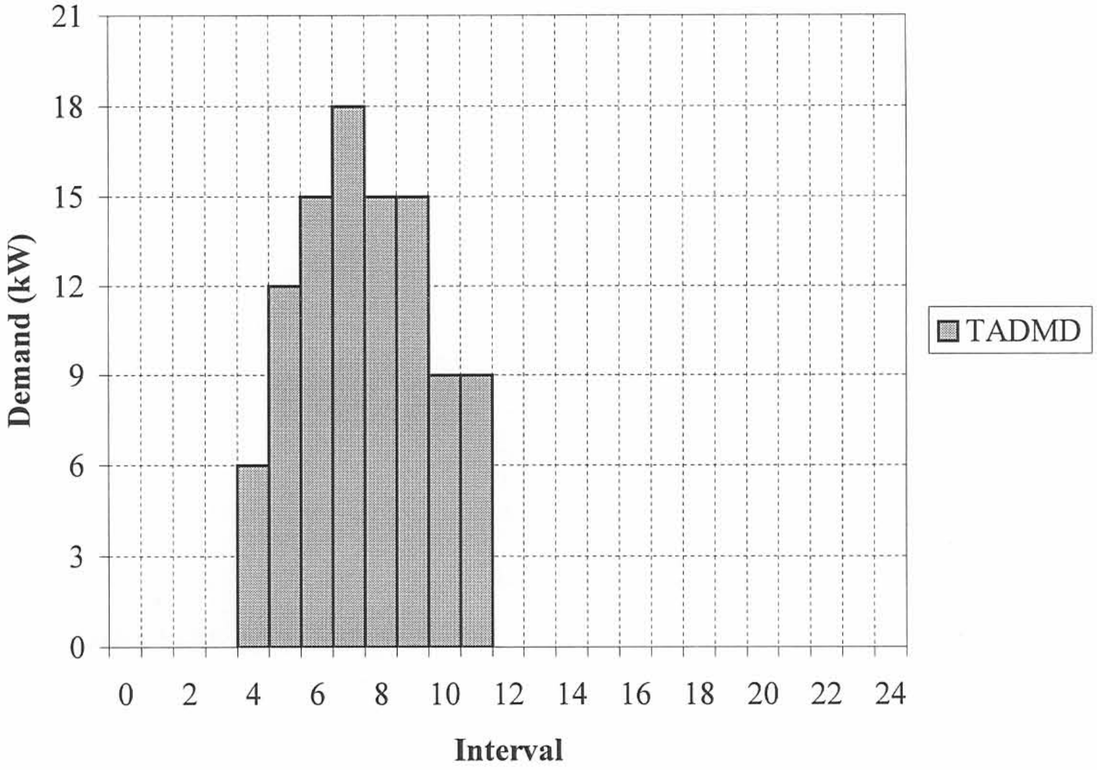


Figure 3.2: TADMD-profile of a group of eight hot water cylinders.

The following global assumptions have to be made to simplify the illustrations, but they will not necessarily influence the load reaction model as such. The assumptions are that:

- The group of cylinders consists of 8 members,
- Each with an element rating of 3kW,
- All at the same ambient temperature of 20°C,
- With a fixed thermostat level,
- No thermal losses and
- The cylinder is ON for an entire interval, with no switching within an interval.

From figure 3.2 one is able differentiate the exact amount of cylinders that consumed energy within a specific interval. The next experiment will prove that the most important information for HWLC-purposes is actually the composition of cylinders within a specific interval and not necessarily the shape of the TADMD itself.

3.1.2 The Need To Know The Exact Consumption Pattern

Let's assume for a moment that it is possible to extract the cylinder consumption pattern as illustrated in figure 3.3 and figure 3.5. Shading options are used in the TADMD to illustrate the contribution of various cylinders where applicable. The options are:

- ☐ The grey area that indicates a "don't care" status – these consumption patterns have no effect on the CLP or load normalisation periods and
- ☐ The solid colours signifies the allocated energy for load shifting purposes.

The experiment is started off by selecting two TADMD-profiles, equal in shape, with different consumption patterns embedded within intervals 11 and 12. In consumption pattern A, during intervals 10 and 11, there is a total of 6 different cylinders (Cyl A – Cyl F) that consumes energy. In pattern B only 3 cylinders (Cyl A- Cyl C) are in the ON state but their energy are consumed over of two intervals.

To illustrate the effect of the slight difference in consumption patterns, all the cylinders are switched off simultaneously at the end of the 9th interval and restored again at the start of the 12th. With the assumption that conversion of energy applies, the hot water cylinder simulator software can construct the load reaction curves as portrayed in figure 3.4 and figure 3.6. The simulator software routine is quite simple and it only has to conform to the following rules:

- ☐ The same amount of blocks of energy for each cylinder that was removed must be replaced after the load has been restored.
- ☐ Only one block per cylinder is allowed in an interval because a cylinder element consumes energy at a constant rate of 3kW per interval.

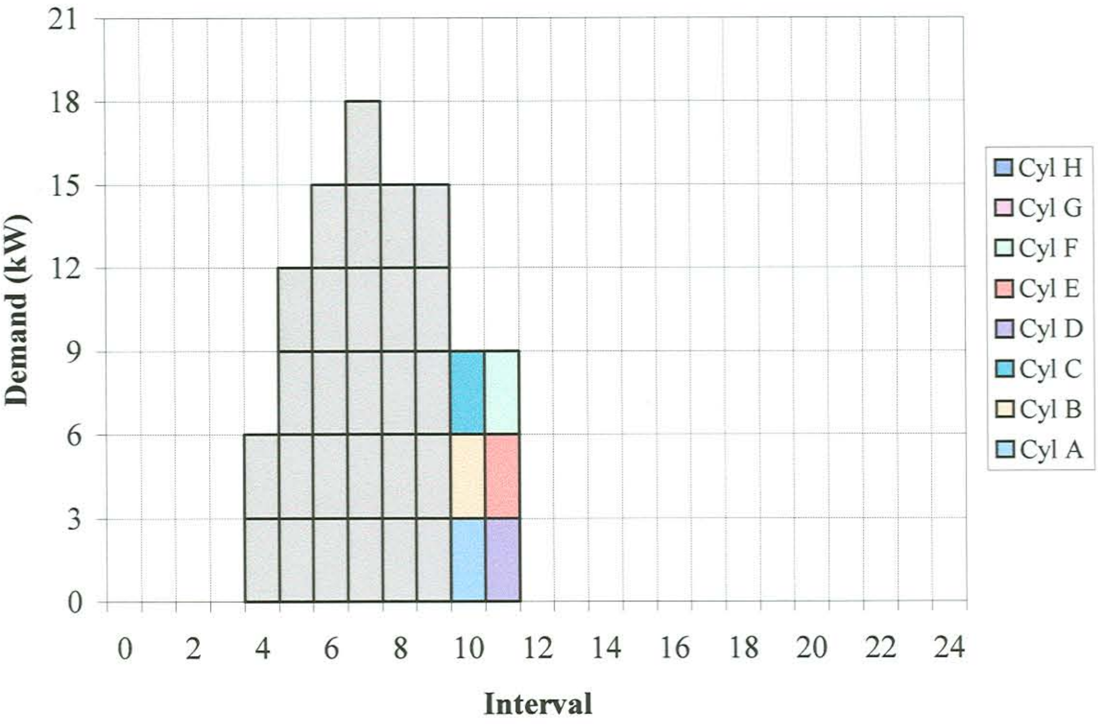


Figure 3.3: Hot water cylinder consumption pattern A.

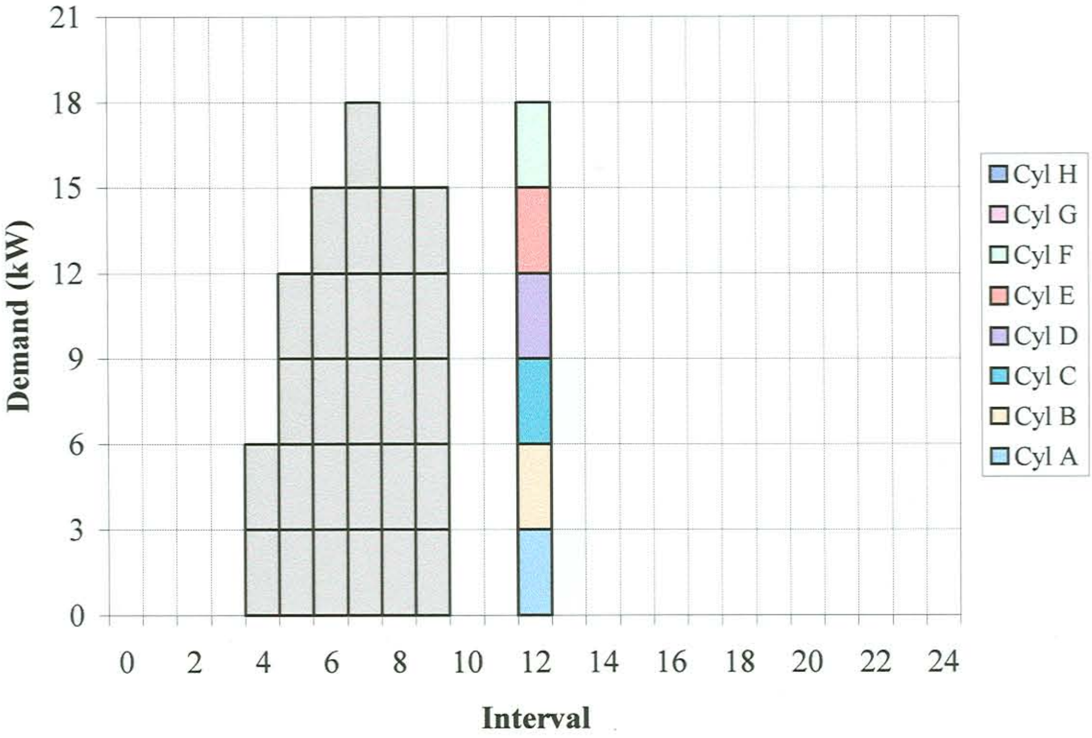


Figure 3.4: Load reaction of consumption pattern A to load curtailment.

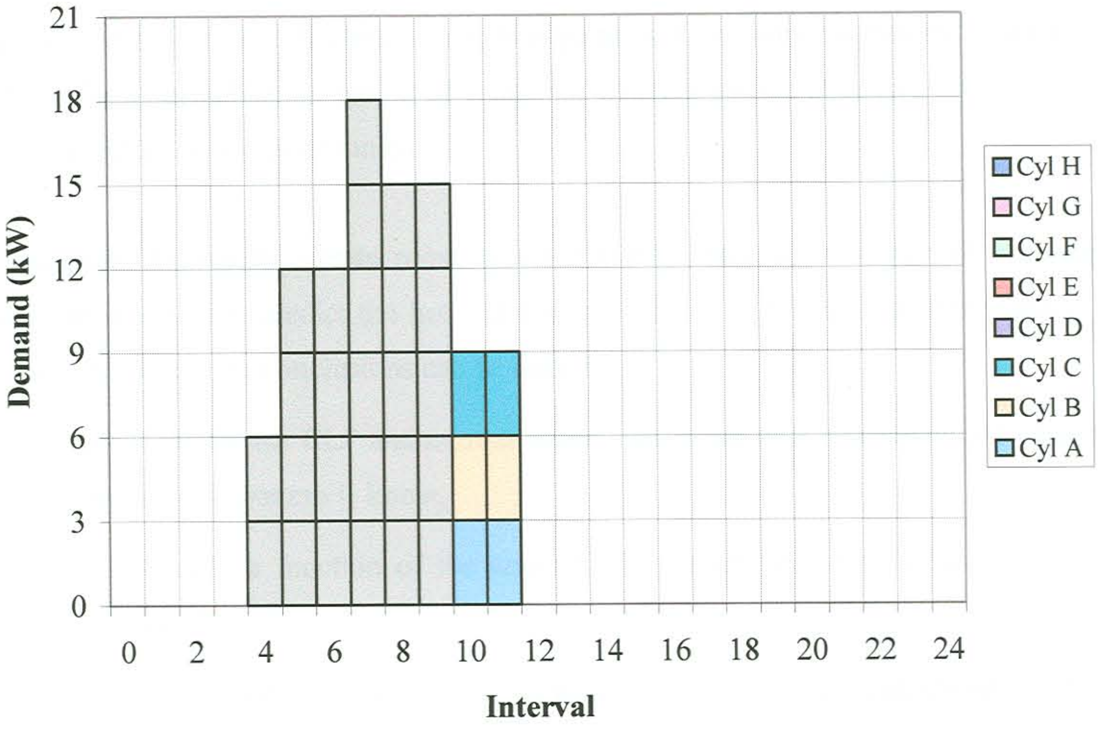


Figure 3.5: Hot water cylinder consumption pattern B.

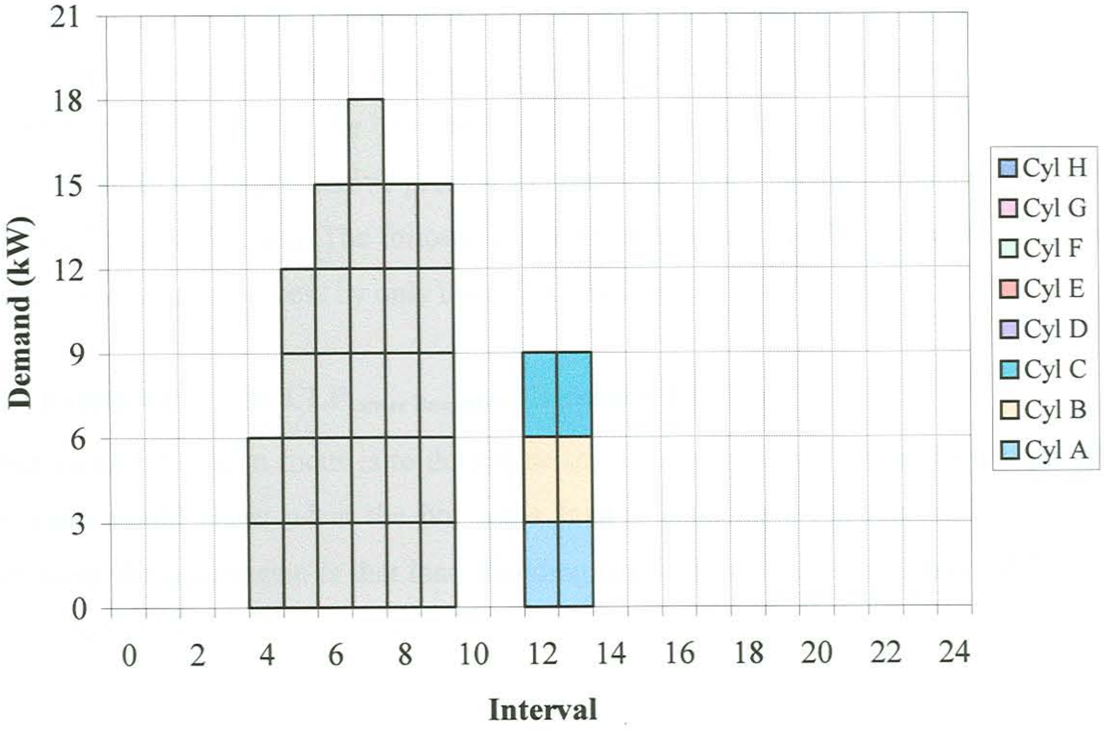


Figure 3.6 Load reaction of consumption pattern B to load curtailment.

The simulated results clearly illustrate that one TADMD can have multiple outcomes, depending on the actual cylinder consumption patterns. Consumption pattern A had a CLP of 18kW for a normalisation period of 1 interval whereas pattern B caused a CLP of 9kW within the same control environment.

Unfortunately the results clearly prove that a TADMD used on its own will not supply enough information to predict the hot water load reaction as result of applied control. At this stage the following conclusions can be drawn:

- ☐ An exact value for the CLP and normalisation curves can only be determined when the load consumption pattern is know,
- ☐ The CLP is only a function of the amount of cylinders that would have consumed energy during T_{Shed}.
- ☐ The load normalisation curve can be constructed by using the calculated CLP, the amount of energy extracted during T_{Shed} and the real-time consumption during normalisation.

At present no means exist to determine the exact hot water consumption patterns. The only other alternative is to define ways that enables one extract the information within a TADMD-profile to full. At the University of Pretoria successful studies on TADMD data have resulted in a comprehensive process to predict the load reaction boundaries as result of a specific control action. The following experiments will guide the reader to understand the reasoning behind process by only using TADMD data.

3.1.3 Formulating The $CLP_{Lower Boundary}$ Extraction Process

In this section the main focus is to determine the conditions in which the lowest possible CLP value could occur when the hot water load is shed for a specific period. For this experiment the assumption is that load shedding occurs from the start of interval 7 till the end of interval 11.

The load reaction and reconstruction simulation was done on an iterative process until the boundary conditions occurred. The process to determine the lowest possible CLP for any situation can then be formulated by studying the TADMD conditions in which the lower boundary occurred.

From the TADMD of figure 3.1, it is possible to calculate the amount of cylinders that intended to consume energy during no-control conditions. The calculations showed that:

- 6 cylinders consumed energy in interval 7,
- 5 cylinders in interval 8,
- 5 cylinders in interval 9,
- 3 cylinders in interval 10 and
- 3 cylinders in interval 11.

The simulation results showed that the $\text{CLP}_{\text{Lower Boundary}}$ is in a sense visible with the naked eye. Results confirmed that the $\text{CLP}_{\text{Lower Boundary}}$ for the selected shedding period is fixed at 18 kW due to the consumption in 7th interval and is illustrated in figure 3.7 and figure 3.8.

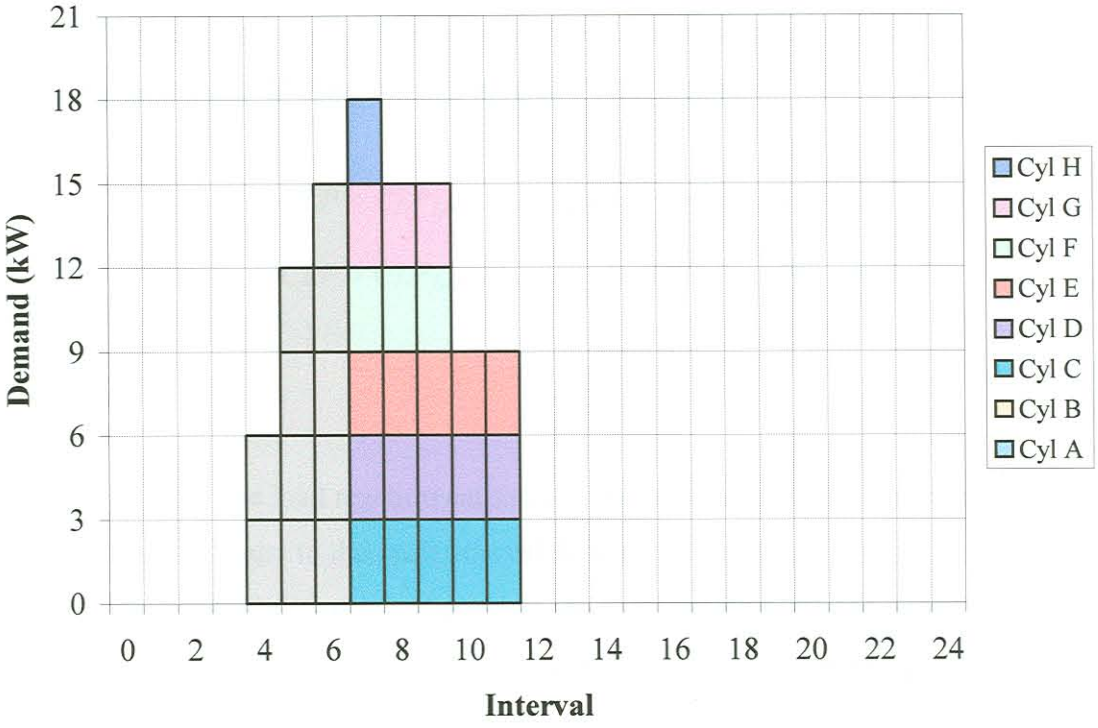


Figure 3.7: Consumption pattern for lower boundary illustration.

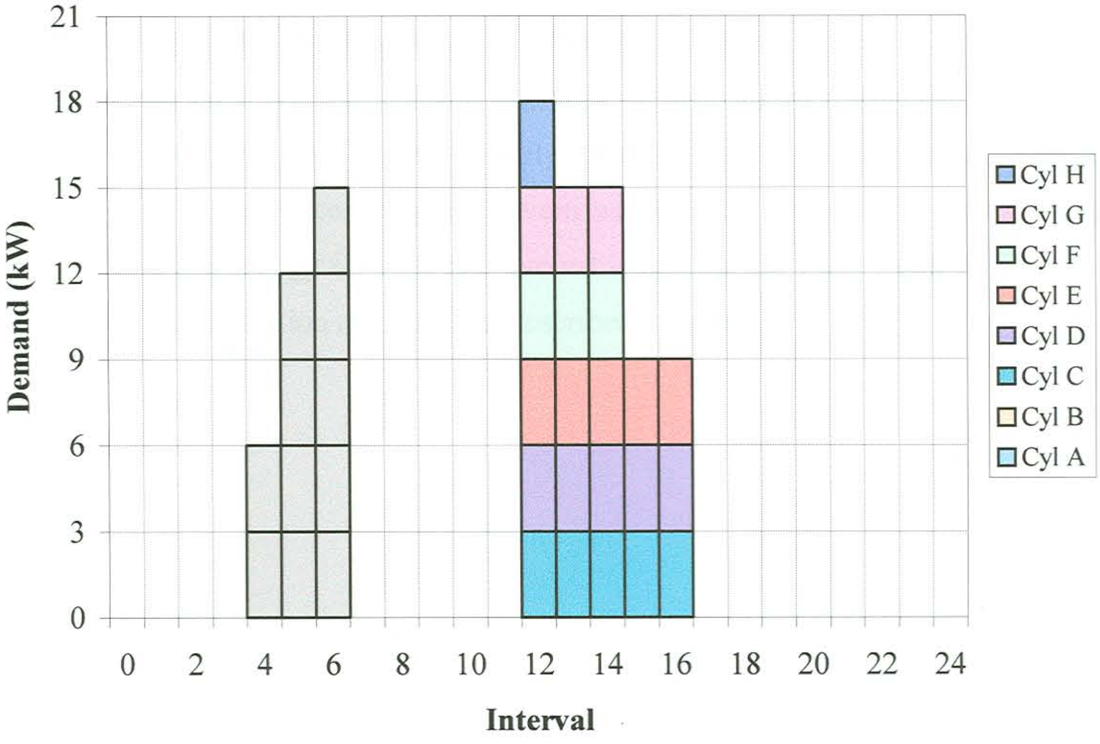


Figure 3.8: Lower boundary load reaction illustration.

The CLP can only be equal to the lower boundary when the cylinders in the peak demand interval coincides with the total population of cylinders that intended to consume energy during the entire T_{Shed}. Mathematically it can be described as:

$$CLP = CLP_{Lower\ Boundary} \text{ when } B = A \cap B \tag{3.1}$$

$$CLP > CLP_{Lower\ Boundary} \text{ when } B > A \cap B \tag{3.2}$$

where,

CLP	The load reaction caused by control actions for the period of T_{Shed}.
$CLP_{Lower\ Boundary}$	Equal to the peak interval demand during T_{Shed}.
A	Population of cylinders in the peak demand interval during T_{Shed}.
B	Population of cylinders that intended to consume energy during T_{Shed}.

Now that $CLP_{Lower\ Boundary}$ is fixed, the next step is to determine if a $CLP_{Higher\ Boundary}$ calculation process can be formulated.

3.1.4 Formulating The $CLP_{Higher\ Boundary}$ Extraction Process

Undoubtedly, the worst possible scenario in HWLC is when all the energy extracted during T_{Shed} is consumed during the interval directly after the load has been restored. This can only be possible when the consumption pattern was of such a nature that every cylinder intended to consume energy for only one interval length during T_{Shed}. Refer to figure 3.4, on page 63 for the simulation results of the described scenario.

Mathematically the higher boundary can be determined by:

$$CLP_{HigherBoundary} = \sum_{n=t_{shed}}^{t_{restore}} TADMD(n) \tag{3.3}$$

with,

$CLP_{Higher\ Boundary}$	Realistically the highest possible value of the CLP.
n	Timeslot or interval number.
t_{shed}	Timeslot or interval number in which shedding occurred.
$t_{restore}$	Timeslot or interval number in which restoring occurred.
$TADMD(n)$	The TADMD for the n^{th} timeslot or interval.

In theory this equation is true, but the calculated values seem outrageous when shedding occurs over long periods. Another possible boundary is the installed capacity and the limitation it puts on the calculated $CLP_{Higher\ Boundary}$. Equation 3.3 cannot be true when more energy is extracted during T_{Shed} than what all the controlled cylinders in the system is capable of consuming during one time interval. This phenomenon is clearly illustrated in figure 3.9 and figure 3.10.

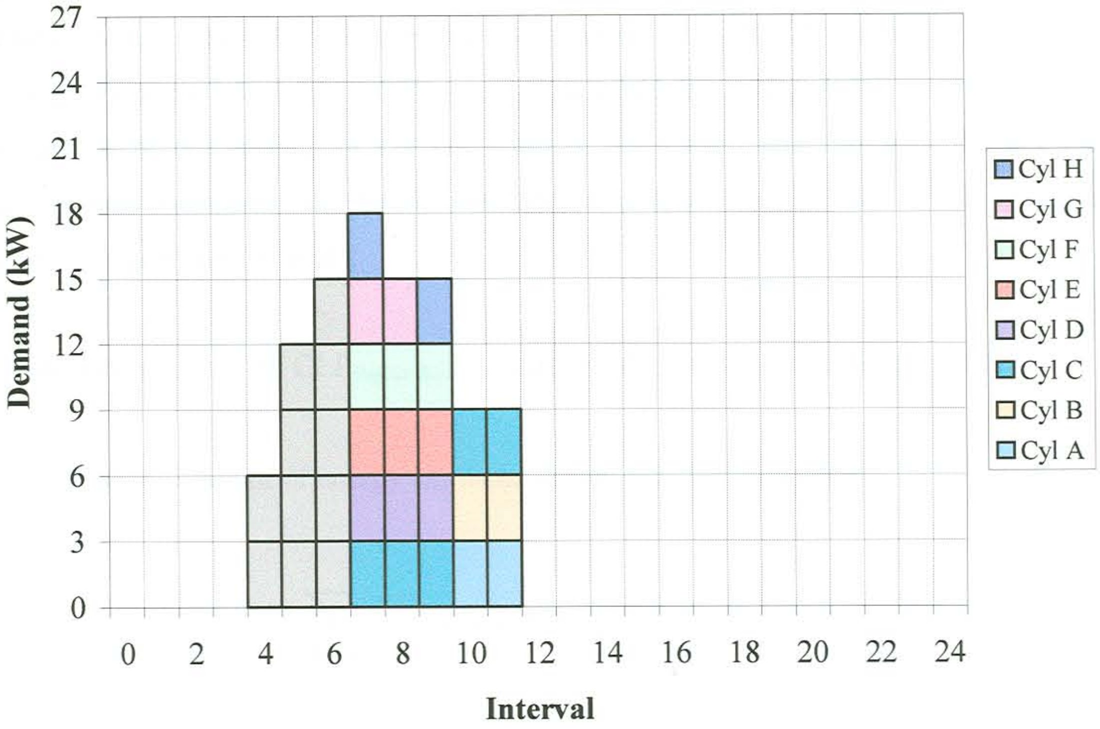


Figure 3.9: Consumption pattern for clipped higher boundary illustration.

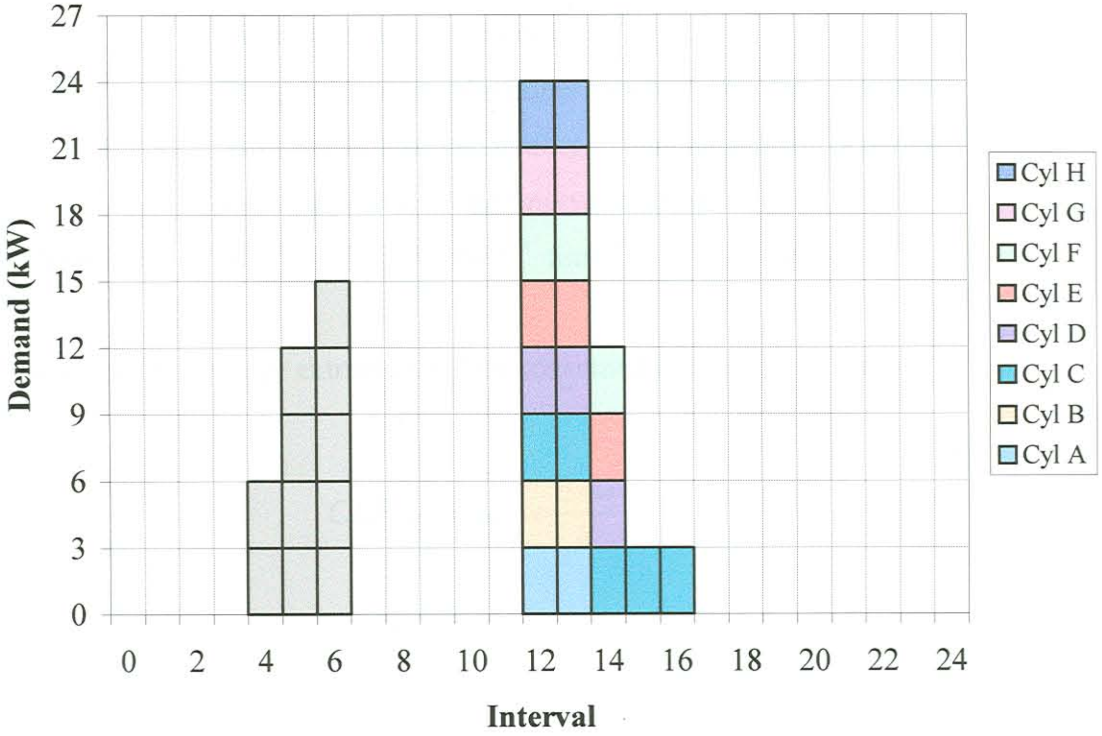


Figure 3.10: Load reaction pattern, illustrating clipping at installed capacity.

The predefined TADMD shape illustrated in figure 3.2 indicates that 22 blocks of energy will be extracted when the cylinders are switched off from the 7th till the 12th interval. In this case, equation 3.3 yields a $CLP_{\text{Higher Boundary}}$ of 66 kW (22 x 3kW) but the system is only capable of consuming 24 kW per interval. No matter what happens, the hot water system cannot consume more than its installed capacity per interval and in this example it is equal to 24 kW per interval.

With the data at hand, the $CLP_{\text{Higher Boundary}}$ can be calculated by following procedure:

(1) Calculate the amount of energy extracted during the shedding cycle.

$$E_{Shed} = \sum_{n=t_{shed}}^{t_{restore}} k \times TADMD(n) \tag{3.4}$$

where,

E_{Shed}	The amount of energy extracted as result of HWLC (J).
n	Timeslot or interval number.
t_{shed}	Timeslot or interval number in which shedding occurred.
$t_{restore}$	Timeslot or interval number in which restoring occurred.
k	Constant value of one interval or timeslot (s).
$TADMD(n)$	The TADMD for the nth timeslot or interval (W).

(2) Assume all the energy extracted will be consumed in one interval only.

$$CLP_{HigherBoundary} = \frac{E_{Shed}}{k} \tag{3.5}$$

(3) Calculate the installed capacity for the amount of cylinders that has been switched off during the shedding cycle.

$$P_{Installed} = \sum_{m=1}^{A} P_{Cyl}(m) \tag{3.6}$$

(4) The $CLP_{Higer\ Boundary}$ calculated in equation 3.5 cannot be greater than $P_{Installed}$. If it is the case then $CLP_{Higer\ Boundary}$ must be set equal to $P_{Installed}$.

Up till now in this section, the load normalisation materialised at a time when no additional consumption occurred. It could also be stated mathematically to say that the normalisation occurred during a period when the TADMD was equal to zero. Therefore the final phase would be to demonstrate the effect of real-time consumption during the load normalisation cycle.

3.1.5 The Effect Of Real-Time Consumption During Load Normalisation

Before this experiment can be conducted, the hot water cylinder simulator software has to be updated with a new rule to minimise confusion and to ease the description of the load reaction profile:

> ***"During the load normalisation cycle the real-time consumption has priority over the shifted load."***

This addition only implies that real-time consumption is indicated on the load reaction curve at the time when it occurred. The shifted energy on the other hand can only be replaced when its allocated cylinder is not in use. From here on the consumption pattern shading also has to change a bit to accommodate the new simulation process.

The shading options used in the TADMD are:

- ☐ The grey area that indicates a "don't care" status – these consumption patterns have no effect on the CLP or load normalisation periods,
- ☐ Solid colours signify the allocated energy for load shifting purposes and
- ☐ The diagonal shading interval that represents the real-time consumption during the load normalisation period.

Figure 3.11 depicts the changes made and figure 3.12 is the result of the simulated shedding of the 10th interval.

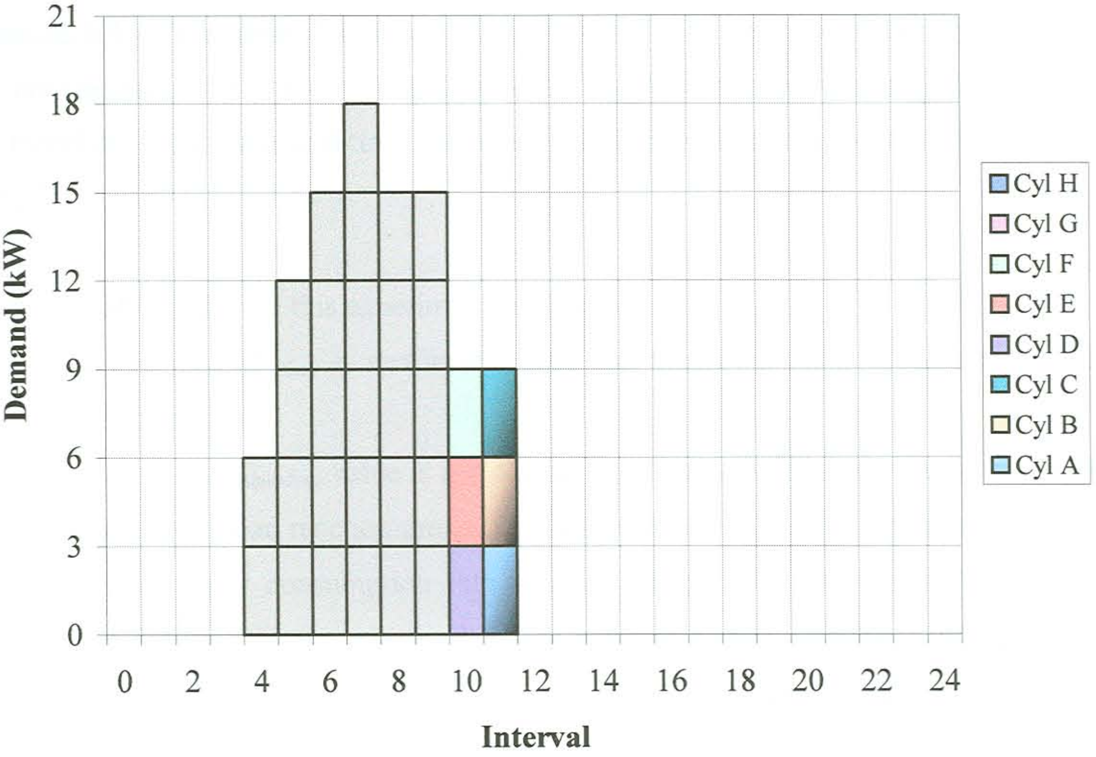


Figure 3.11: Consumption pattern illustrating controllable and real-time energy.

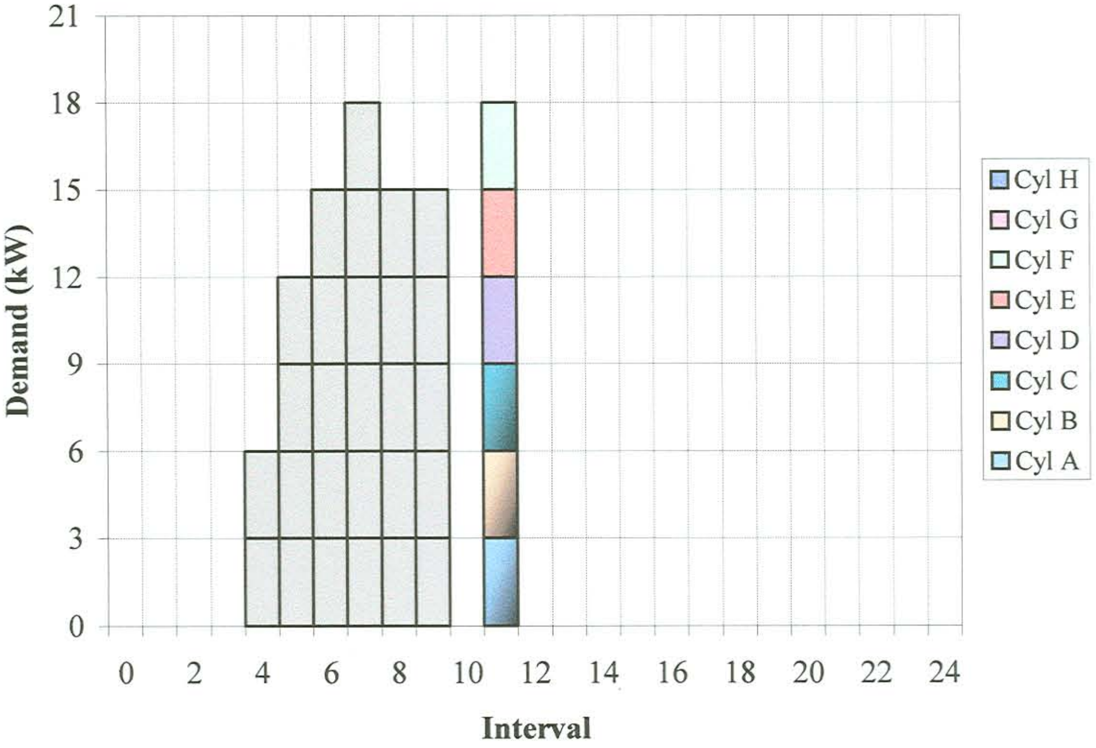


Figure 3.12: Load reaction profile when real-time consumption is taken into account.

The $\text{CLP}_{\text{Higher Boundary}}$ procedure is not yet complete because the procedure defined by equations 3.4 - 3.6 estimated that the highest possible CLP would be equal to 9 kW, which it is not the case. The real-time consumption in the 11th interval causes a CLP of 18 kW and therefore should the real-time consumption after load restoration also be taken into account.

The results obtained from this experiment are twofold:

- The $\text{CLP}_{\text{Lower Boundary}}$ is unaffected since real-time consumption can only increase the load reaction.
- The $\text{CLP}_{\text{Higher Boundary}}$ value is not correct and therefore does real-time consumption influence the load reaction profile. It is therefore better to take the effect of the real-time hot water consumption into account when predicting the higher boundary value during load restoration. The load reaction higher boundary ($\text{LR}_{\text{Higher Boundary}}$) can therefore be seen as the combined effect of CLP and real-time consumption.

The effect of the installed capacity on the $\text{LR}_{\text{Higher Boundary}}$ must be evaluated again before any final conclusions can be made. The next set of consumption patterns, figure 3.13 and figure 3.14, only illustrates that the clipping effect occurs again at the installed capacity level, even with real-time control taken into account.

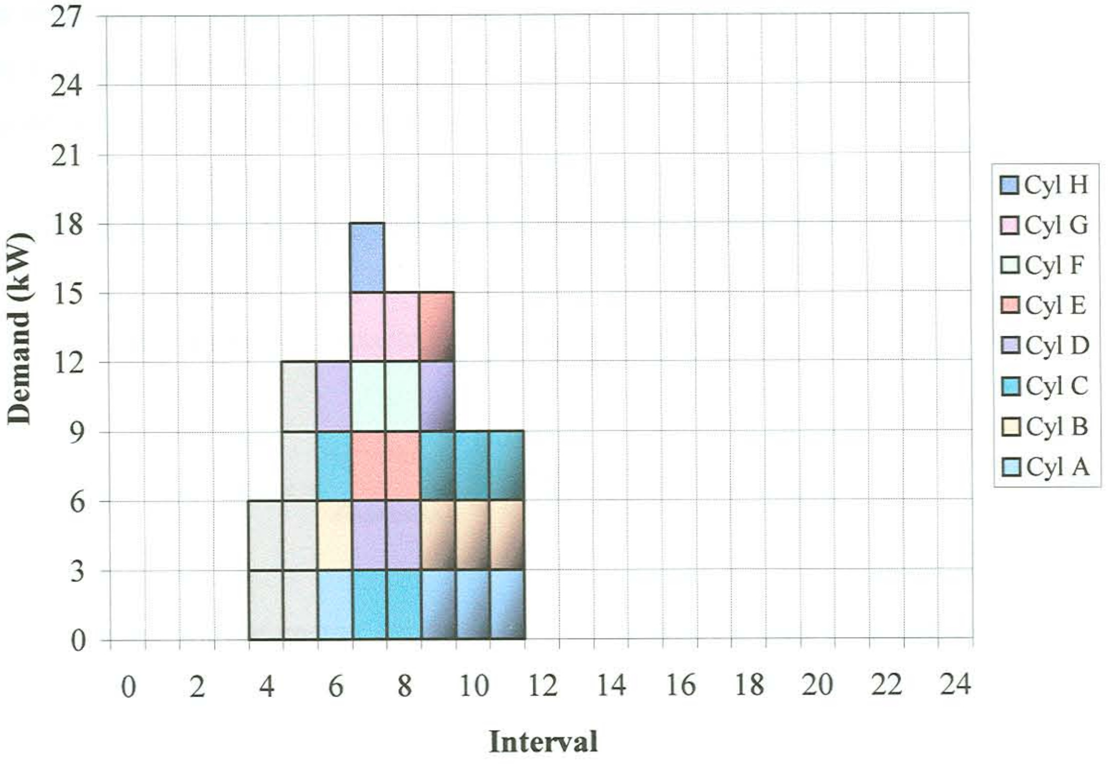


Figure 3.13: Cylinder consumption pattern for shedding intervals 6,7 and 8.

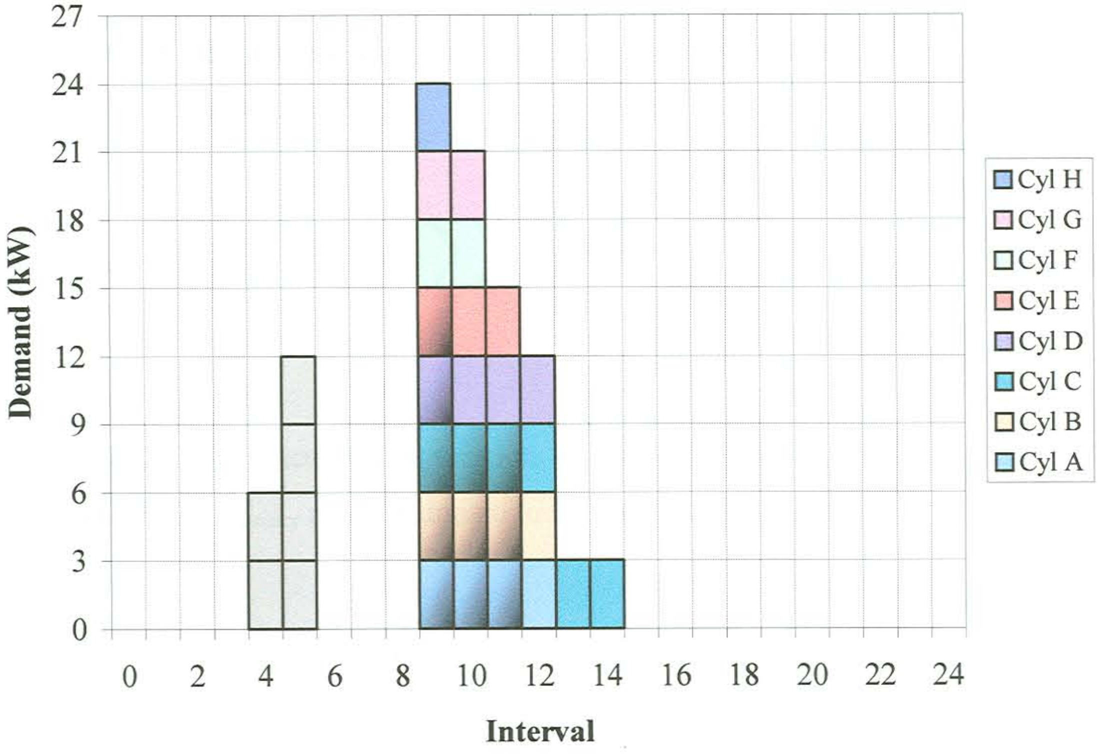


Figure 3.14: Load reaction profile illustrating clipping when real-time consumption is taken into account.

This concludes the work done on the load reaction boundary estimation process. The tests done to date proved that it is possible to predict the load normalisation boundaries while the load consumption patterns are not yet known.

In summary, the higher boundary can be calculated by following procedure:

(1) Calculate the amount of extracted energy during the shedding cycle.

$$E_{Shed} = \sum_{n=t_{shed}}^{t_{restore}} k \times TADMD(n) \tag{3.7}$$

(2) Assume that all the energy extracted as well as the real-time consumption within the restoration interval ($t_{restore}$) will be consumed in one interval only.

$$LR_{HigherBoundary} = \frac{E_{Shed}}{k} + TADMD(t_{restore}) \tag{3.8}$$

(3) Calculate the installed capacity for the amount of cylinders that has been switched off during the shedding cycle.

$$P_{Installed} = \sum_{m=1}^{A} P_{Cyl}(m) \tag{3.9}$$

(4) The $LR_{Higer\ Boundary}$ calculated in equation 3.8 cannot be greater than $P_{Installed}$. If it is the case then $LR_{Higer\ Boundary}$ must be limited to the value of $P_{Installed}$.

3.1.6 Model Implementation And Verification

The entire population of the hot water cylinders installed at the University of Pretoria is not enough to accurately represent a municipal environment. Therefore actual municipal data has been obtained from Eskom to ensure that the model verification is accurate and true.

During 1999, Eskom conducted a series of test from Monday, August 9 till Friday, August 13 on one of their newly installed HWLC-systems. The selected area is one of the fastest growing urban residential areas in South Africa with an exceptionally high population density factor. Personal comfort is in the order of the day since most of the consumers earn more than the average baseline, which explains why the cylinder ratio per household is equal to 1.27.

For the experiments conducted by Eskom, specified in table 3.1, 9,000 HWLC-units were used to determine the hot water dynamics of the area and effects of human behaviour on the HWLC-system.

Table 3.1: Schedule for tests conducted during August 1999.

Day	Description	Action
Monday	AMD for a public holiday	Notch on the ½ hour
Tuesday	ADMD for a weekday	Notch on the ½ hour
Wednesday	Emergency Interrupt Test	Shed all from 7:00 – 9:00
Thursday	Real Time Pricing Schedule	Shed all from 6:00 – 8:00
Friday	Wholesale Electricity Tariff Schedule	Shed all from 7:00 – 10:00

Aim Of The Study

The aim of this study is to use the data gathered during the tests conducted on Tuesday and Wednesday, and apply it to the CLP unit of the load reaction model. The procedure to calculate the higher and lower boundaries will be illustrated and then compared to the actual results obtained.

The notch test conducted on Tuesday, figure 3.15, can be used to construct a regular weekday TADMD-profile for the month of August, shown in figure 3.16. On Wednesday morning the entire controllable load of 9,000 cylinders were switched off at 7:00 and then restored again at 9:00. The load reaction curve was recorded and will be used to compare the actual values with the output predicted by the load reaction model.

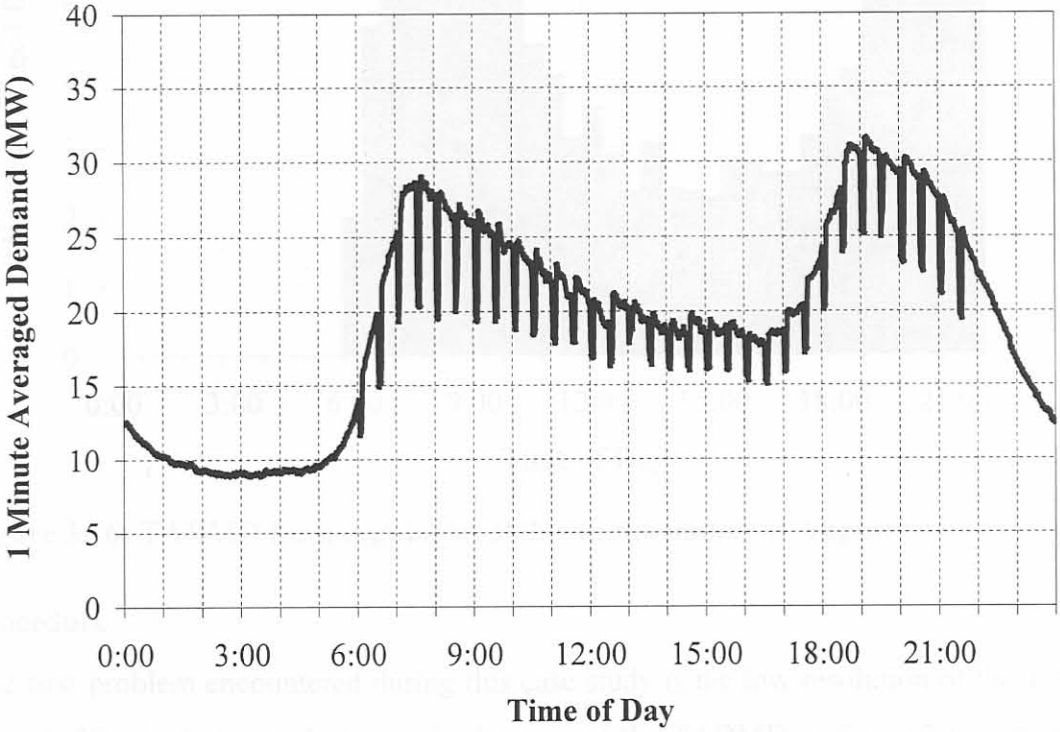


Figure 3.15: Notch test results for a regular weekday on Tuesday, 10 August 1999.

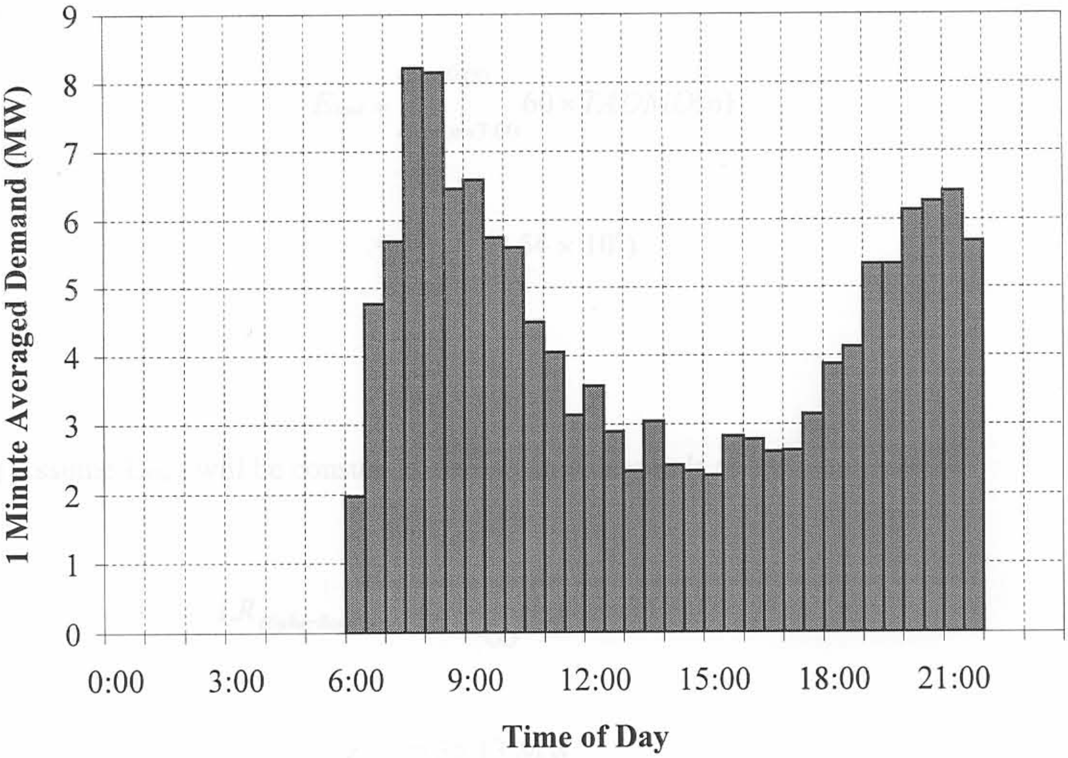


Figure 3.16: TADMD for a regular weekday in the month of August.

Procedure

The first problem encountered during this case study is the low resolution of the TADMD data. A 30-minute interval size, as in the case of the TADMD in figure 3.16, impairs the accuracy and versatility of the prediction process because prediction would preferably be done for every minute.

The one option would be to convert the uncontrollable load from a 1-minute interval size to a 30-minute average demand profile. In this case, it is a plausible option but definitely not versatile since shedding hardly occurs exactly on the half hour. Another option is to assume that the hot water consumption is constant between half hours and to divide the TADMD into minute intervals.

The $LR_{Lower\ Boundary}$ is always equal to the $CLP_{Lower\ Boundary}$, which in this case is 8.2 MW, found between 7:30 and 8:00. For the sake of the reader, the calculation of the $LR_{Higher\ Boundary}$ will be done step by step to illustrate the process defined in section 3.1.5.

(1) Calculate the amount of energy extracted between 7:00 and 9:00.

$$E_{Shed} = \sum_{n=7:00}^{9:00} 60 \times TADMD(n)$$

$$= 60 \times (28.54 \times 10^6)$$

$$= 1.71 \text{ GJ}$$

(2) Assume E_{Shed} will be consumed entirely in 60 seconds at 9:00.

$$LR_{HigherBoundary} = \frac{1.71 \times 10^9}{60} + 6.59 \times 10^6$$

$$= 35.13 \text{ MW}$$

(3) The assumption is that 9,000 units (3 kW, 150 litre) have been switched.

$$P_{\text{Installed}} = 9000 \times 3000$$

$$= 27 \text{ MW}$$

(4) The $LR_{\text{Higher Boundary}}$ cannot be greater than $P_{\text{Installed}}$ and must therefore be equal to 27 MW.

(5) The base-load at 9:00 is equal to 19 MW, and therefore is the expected consumption for 9:00 between 27.2 MW and 46 MW.

Verification

A demand value of 35.2 MW was reached at 9:00 with a load reaction value of 16.2 MW. It means that only 4,050 of the entire population of cylinders whished to consume electricity between 7:00 and 9:00. The calculated boundaries are within specification, with the predicted lower boundary 51% less and the higher boundary 60% more than the measured load reaction value.

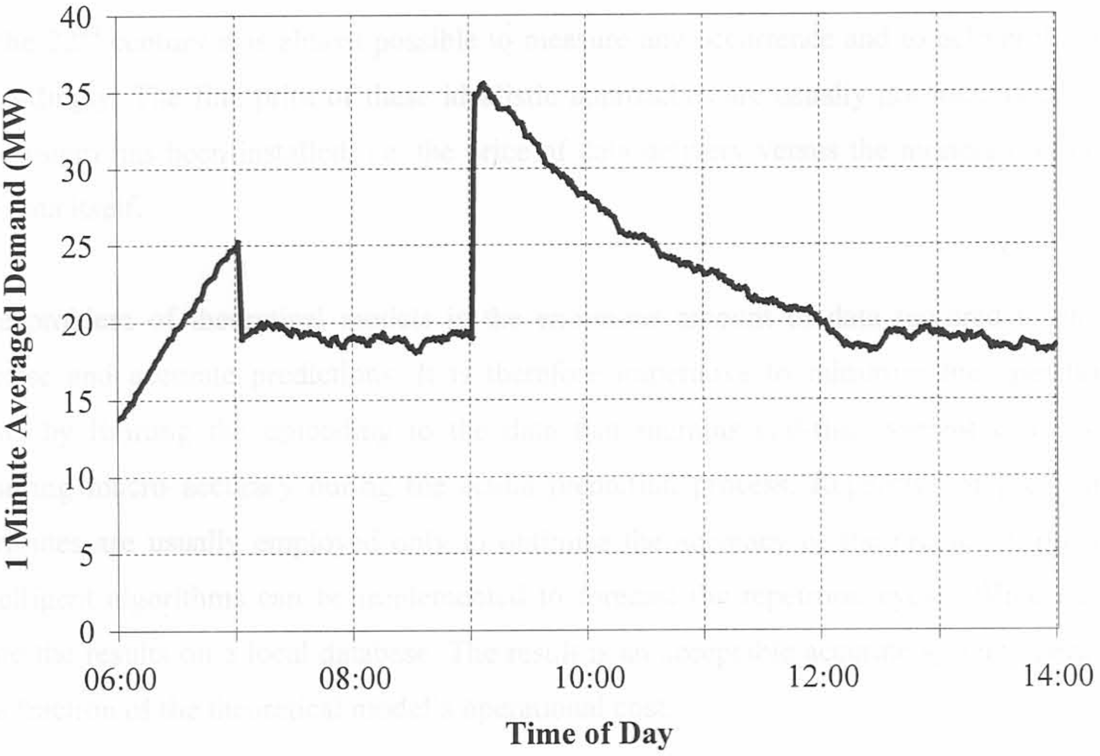


Figure 3.17: Measured load-profile for the Emergency Interrupt Test.

Various ways exist to refine the boundary calculation process and some of the ideas will be discussed in the conclusions section of chapter 5.

3.2 AVERAGE CYLINDER TEMPERATURE PREDICTION MODEL

Cylinder temperature modelling has been a favourite topic among authors [17, 21] at the University of Pretoria. Instead of re-inventing the wheel again, this section would rather focus on the process of implementing and integrating the average cylinder temperature predictions into the end-user model. Various evident pitfalls have been defined and will be outlined before the process definition phase can commence.

3.2.1 Refining The Data

In the 22nd century it is almost possible to measure any occurrence and to deliver the data accordingly. The fine print of these idealistic approaches are usually not mentioned until the system has been installed, i.e. the price of data delivery versus the monetary value of the data itself.

The problem of theoretical models is the enormous amount of data required to ensure precise and accurate predictions. It is therefore imperative to minimise the operational costs by limiting the uploading to the data that ingrains real-time variant constraints, ensuring macro accuracy during the actual prediction process. Repetitive or predictable attributes are usually employed only to optimise the accuracy of the prediction process. Intelligent algorithms can be implemented to forecast the repetition cycle offline and to store the results on a local database. The result is an acceptable accurate system operating at a fraction of the theoretical model's operational cost.

Another pitfall that is usually unattended is the effect of HWLC-actions on the consumer hot water consumption pattern.

3.2.2 Non Linear Consumption Patterns

Temperature prediction models developed by Delport [17], indicates that hot water consumption is non linear when a cylinder is switched off during load-control actions.

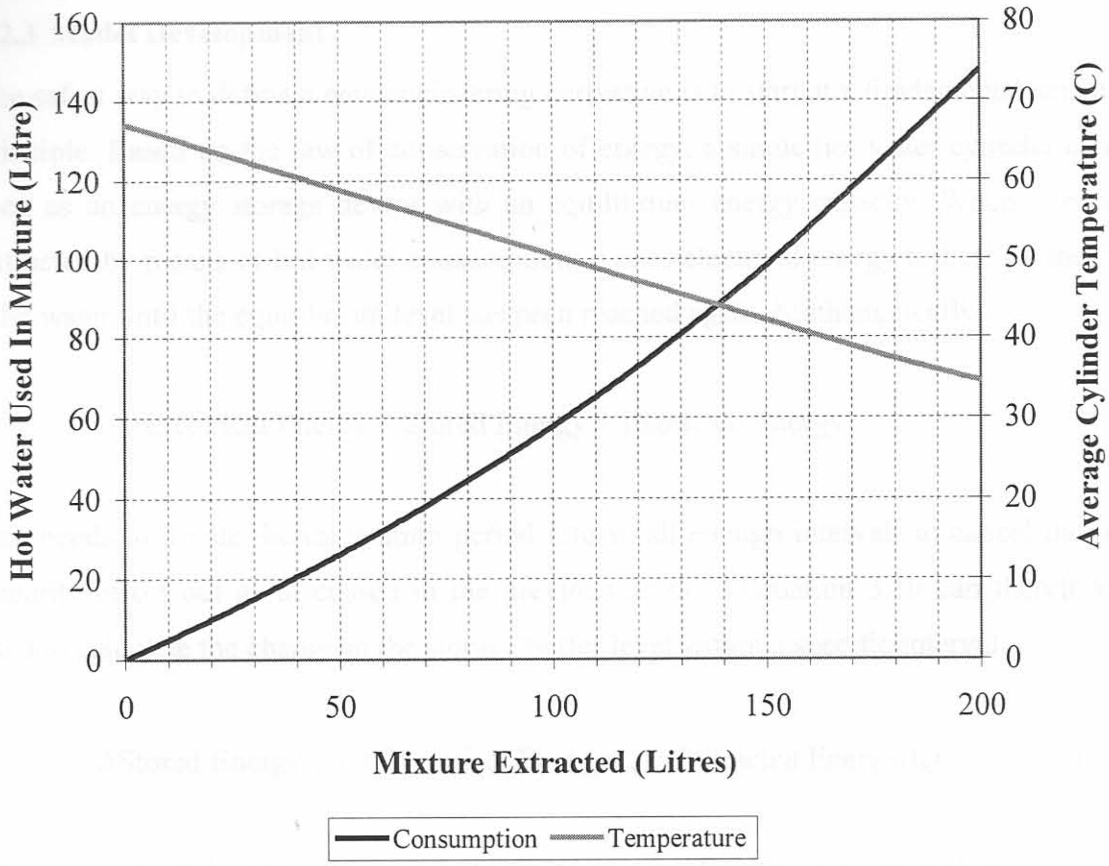


Figure 3.18: Non-linear residential hot water extraction during shedding periods.

Figure 3.18 was generated by the assumption that a residential consumer requested a constant water supply of 10 litres per minute at a mixture temperature of 40°C when taking a shower. The hot water is extracted at an initial temperature of 67 °C and then mixed with the cold water supply to obtain the mixture temperature.

As consumption continues the average cylinder temperature decreases because the HWLC-device has disabled the cylinder's heating element. This decrease in cylinder temperature initiates an increase in the hot water flow rate to maintain a mixture temperature 40°C. Therefore should the non-linear effect be taken into account when predicting the average cylinder temperature.

3.2.3 Model Development

The safest way to define a new engineering derivative is to start at a fundamental scientific principle. Based on the law of conservation of energy, a single hot water cylinder can be seen as an energy storage device with an equilibrium energy capacity. When energy is extracted by means of hot water consumption, it uses electrical energy to heat up the cold inlet water until the equilibrium level has been reached again. Mathematically:

$$\text{Electrical Energy} = \text{Stored Energy} + \text{Extracted Energy} \tag{3.10}$$

One needs to divide the integration period into small enough intervals to cancel the non-linearity effect out as discussed in the previous section. Equation 3.10 can therefore be used to calculate the change in the storage buffer level within a specific interval:

$$\Delta\text{Stored Energy}(t_x) = \text{Electrical Energy}(t_x) - \text{Extracted Energy}(t_x) \tag{3.11}$$

The amount of energy stored in the cylinder is directly proportional to its water temperature and the volume of the cylinder. Therefore, any change in stored energy would be directly responsible for a change in the cylinder temperature.

$$\Delta\text{Stored Energy}(t) = mc\Delta T(t) \tag{3.12}$$

The volume of the water inside the cylinder is also equal to the mass required for equation 3.12 because one litre of water weighs approximately one kilogram and the specific heat of water, c, is equal to 4,200 K/kg/°C.

The next step is to evaluate the energy extracted out of the cylinder. According to the theoretical model developed by Delport [17], it is mainly a function of:

- ☐ Water consumption patterns,
- ☐ The temperature of the water inside the cylinder,
- ☐ Inlet water temperature,
- ☐ Piping - and insulation losses and
- ☐ The cylinder orientation.

It is almost impossible, and definitely impractical to measure all the inputs individually. The data refinement process, discussed in section 3.2.1, has initiated the search for a cost effective solution.

Chapter 1 has shown that notch test data is a fair resemblance of the total amount of energy extracted out of the system. The TADMD-profiles have already been stored for the load reaction module and can just as well be used by the temperature prediction process. The extracted energy for a specific user group can therefore be calculated by using equation 2.2 on page 56:

$$\text{Extracted Energy}(Group, t_x) = Interval\ Size \times \text{TAMD}(Group, Day, Month, t_x)$$

The electrical energy consumed during a specific interval is a function of the:

- ☐ Element rating,
- ☐ The thermostat status (On or Off) and
- ☐ The HWLC-unit status (Shed or Restore)

Yet again is the value of measurement not viable and the requirement is to find an accurate representation of the real-time hot water electricity consumption. The only phrase that comes to mind is déjà vu. The output of the load reaction model embodies all of the above variants and therefore can the electrical energy consumed by a user group during any specific time interval be obtained by:

$$\begin{aligned}\text{Electrical Energy}(\mathit{Group}, t_x) &= \mathit{Interval\ Size} \times \text{Real-time Consumption Pattern}(\mathit{Group}, t_x)\\ &= \mathit{Interval\ Size} \text{ x } \text{Load Reaction Profile } (\mathit{Group},\ t_x)\end{aligned} \qquad (3.13)$$

The results obtained can now be substituted into equation 3.11 to attain the final equation relating the change in average cylinder for a specific user group and interval.

$$\Delta T(t_x) = \frac{IntervalSize}{mc} \times RTConsumption(Group, t_x) - TADMD(Group, Day, Month, t_x)$$

The average cylinder temperature can be obtained by:

$$T(t_x) = T(t_0) + \sum_{n=1} \Delta T(t_n) \qquad (3.14)$$

There is no need to verify the model since it is based on previous work done, along with basic scientific principles. An illustrative example follows, which will guide the reader through the process again to clarify any uncertainties.

3.2.4 Model Implementation

Now that the model has been defined and refined, it is possible to implement it into a real life scenario. The object of the model is not necessarily to predict the average cylinder temperature, but rather to predict the time of day that the risk of cold water could occur. In other words, estimations are made to ensure that the average cylinder temperature is never below the level specified by the management rules

Aim Of The Study

For this example, the model integration will again be illustrated on the data-set used in section 3.1.6 on page 82. This time the idea is to plot the change in average cylinder temperature due to the load-control actions taken at 7:00 and 9:00.

Procedure

The average cylinder temperature prediction model has been defined, but the integration process is not that simple. The data acquisition sequence, illustrated in figure 3.19, has been optimised to ensure that the requests to and from the database are the minimum.

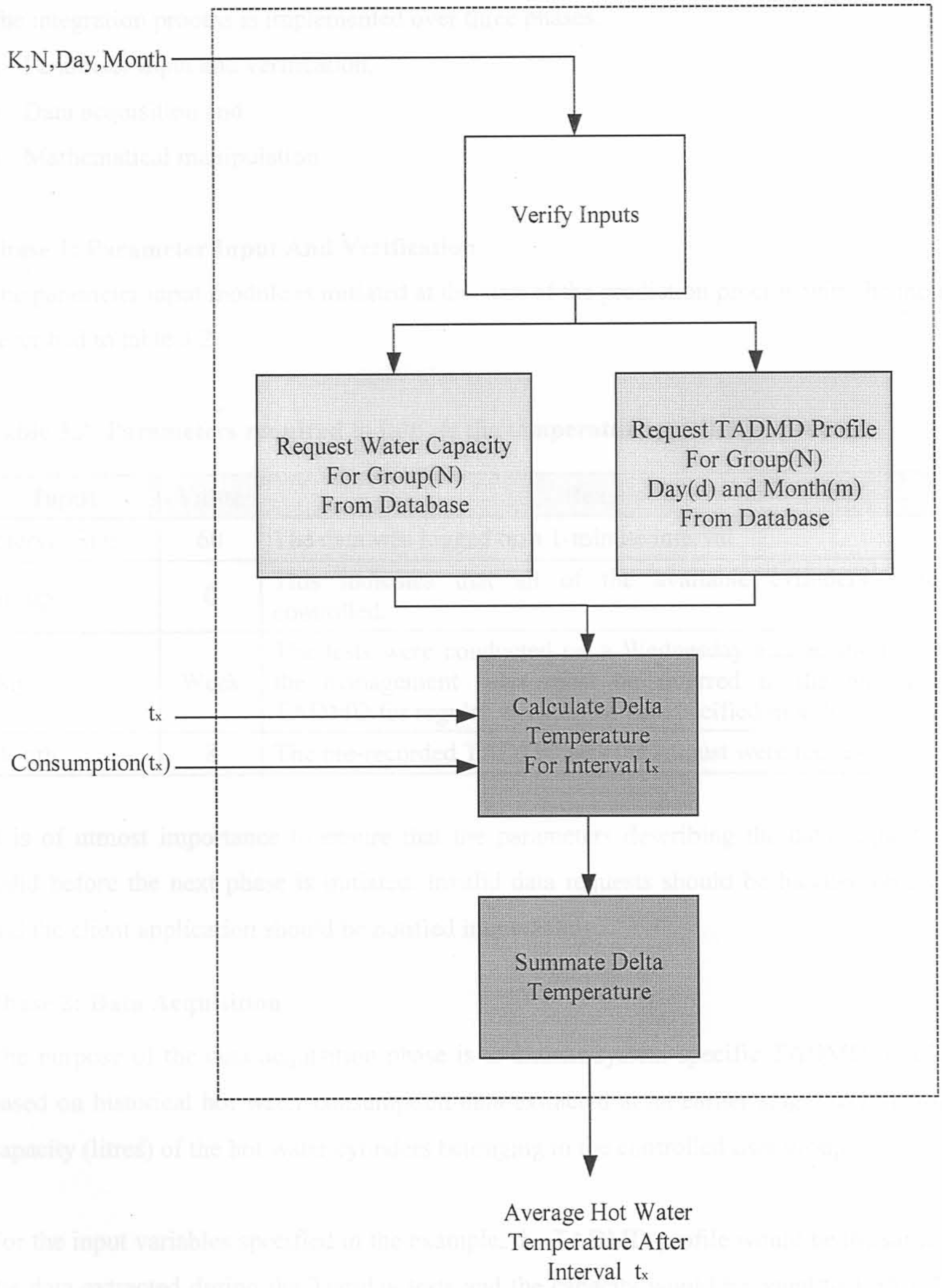


Figure 3.19: Implementation process of the average cylinder temperature prediction model.

The integration process is implemented over three phases:

- ☐ Parameter input and verification,
- ☐ Data acquisition and
- ☐ Mathematical manipulation.

Phase 1: Parameter Input And Verification

The parameter input module is initiated at the start of the prediction process with the inputs described in table 3.2.

Table 3.2: Parameters required to initiate the temperature prediction process.

Input	Value	Reason
Interval Size	60	The data was logged on a 1-minute interval.
Group	0	This indicates that all of the available cylinders were controlled.
Day	Week	The tests were conducted on a Wednesday and according to the management rules must be referred to the recorded TADMD for regular weekday of the specified month.
Month	8	The pre-recorded TADMD sets for August were requested.

It is of utmost importance to ensure that the parameters describing the data request are valid before the next phase is initiated. Invalid data requests should be handled on merit and the client application should be notified immediately.

Phase 2: Data Acquisition

The purpose of the data acquisition phase is to extract system specific TADMD-profiles, based on historical hot water consumption data extracted at an earlier stage, and the total capacity (litres) of the hot water cylinders belonging to the controlled user group.

For the input variables specified in the example, the TADMD-profile would be the same as the data extracted during the Tuesday tests and the capacity would be equal to 1.35×10^6 litre. These values are then stored in memory for future reference throughout the process for this specific day.

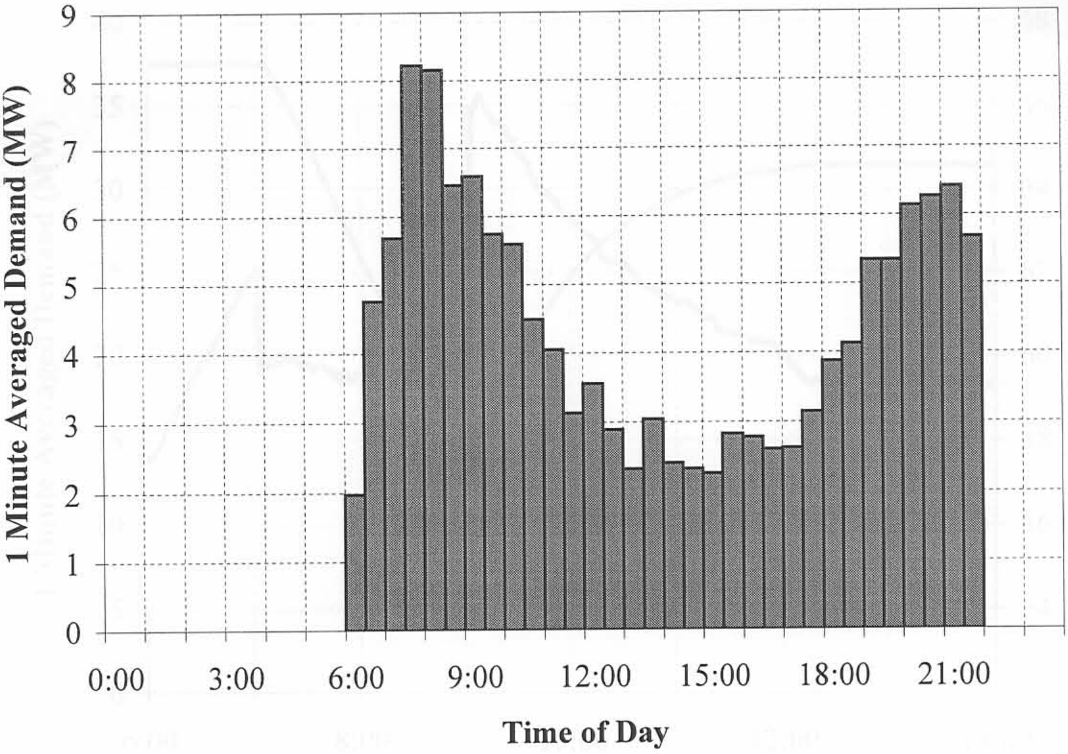


Figure 3.20: TADMD-profile representing the energy available for extraction purposes.

Phase 3: Mathematical Manipulation

The mathematical manipulation phase is an iterative process, running either in real-time as the consumption data becomes available or off-line on historical - and simulated data. The client application must pass the interval number and the user group's real-time consumption value for that specific interval to the calculation module in order to append the group's average cylinder temperature.

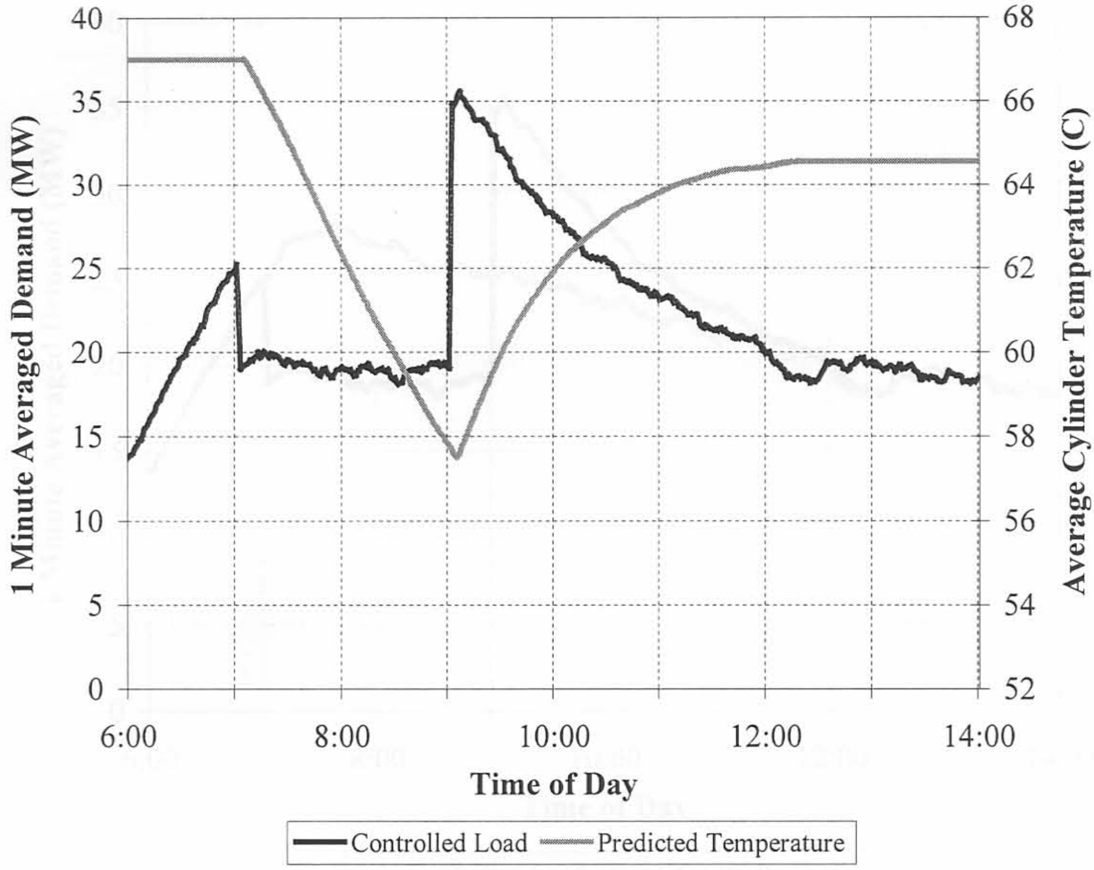


Figure 3.21: Average cylinder temperature prediction model output vs. load-control actions.

Results

The average cylinder temperature drops from 67°C to 57.5°C within the two-hour shedding period and takes more than 2 hours to heat the entire population again. Theoretically the load restoration time should be less than the shedding period, but consumption from various cylinders after restoration hindered the restoration cycle.

One also notices that the model stabilises the prediction temperature at 64.5°C. More energy was extracted during the 2-hour shedding period that what was electrically consumed again during restoration, which is verified by the overlaying illustration in figure 3.22.

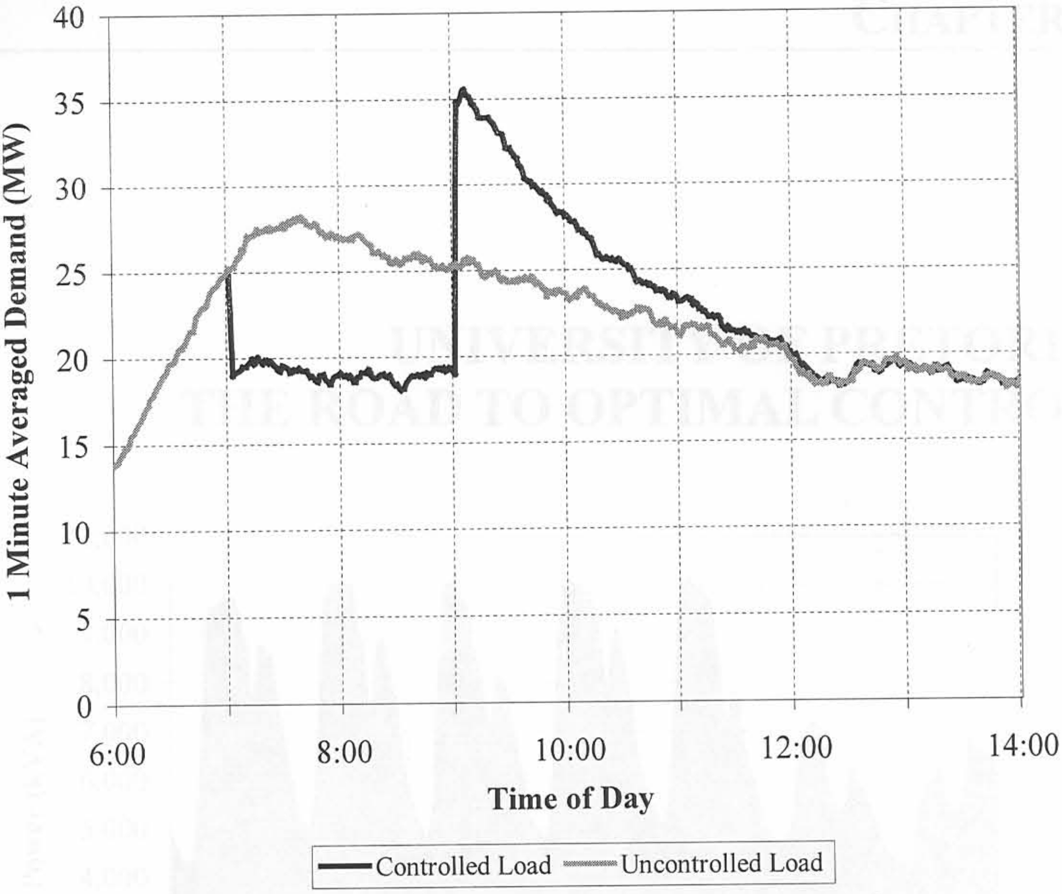


Figure 3.22: Tuesday uncontrolled load portrayed over the controlled load of Wednesday.

Mathematical calculations showed that 53.8 GJ were extracted but only 39.9 GJ were consumed to restore the load. This means that 13.9 GJ were supposed to be delivered but the users had already exhausted their 150-litre supply of hot water within the two-hour period.

The effectiveness of this model is suddenly questionable because certain users experienced cold water while the model predicted a minimum temperature of 57.8°C. The problem at hand is that the temperature prediction was done for the entire population of 9,000 cylinders and not the individual cases. The amount of cylinders used to calculate the mass directly influences the prediction accuracy. The conclusions and recommendations in chapter 5 will take a closer look at ways to optimise the accuracy of the model.

CHAPTER 4

UNIVERSITY OF PRETORIA
THE ROAD TO OPTIMAL CONTROL

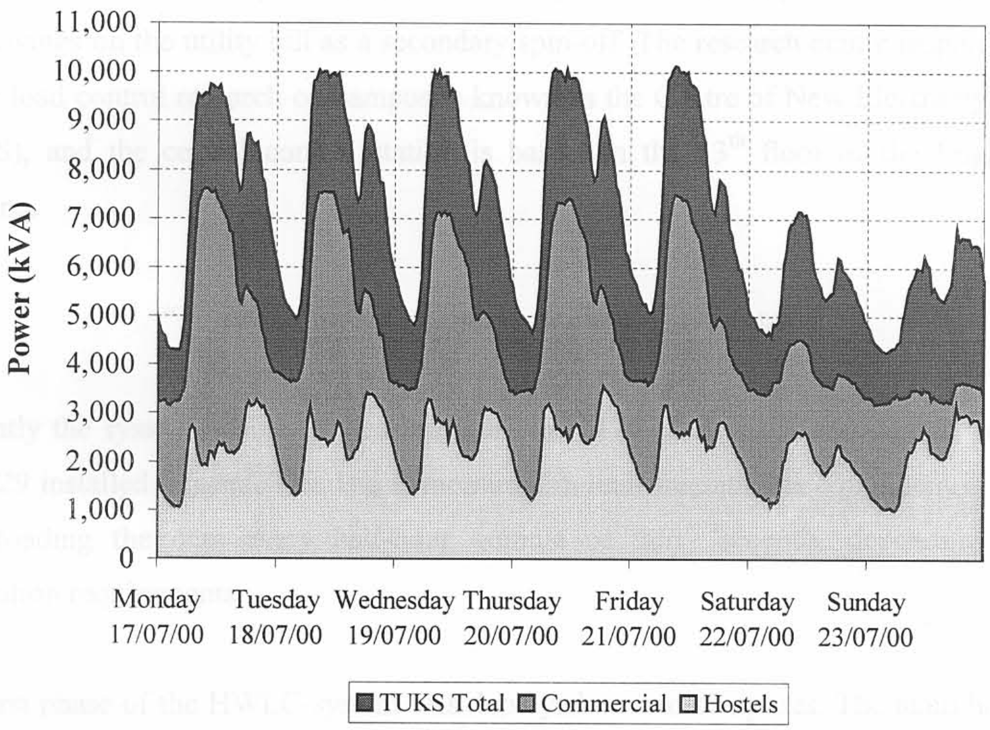


Figure 4.1: Disaggregated load-profile of the University of Pretoria.

The load-profile of the University of Pretoria exhibits the nature of a small town embracing commercial and residential sectors. HWLC at the University of Pretoria is in its fourth year of integration. No expenses have been spared on the implementation of available technology and still no ideal solution has been produced. Development has been done on municipal level with the intention to upgrade the proposal as soon as the utility also supports the drive towards mutual benefit.

This chapter will not walk the mile of the ups and downs experienced to date, but rather portray the real-life application of customer-orientated control.

4.1 END-USER MODEL

The HWLC-system design was based on the end-user model described in section 2.1.1 on page 40. The difference between a good and excellent HWLC-system is availability, accuracy and timely delivery of data. The next paragraph will bring more insight concerning the hardware selected for the University of Pretoria HWLC-system.

4.1.1 System & Process Limitations and Constraints

The role of the University of Pretoria HWLC-system is primarily for research purposes with savings on the utility bill as a secondary spin-off. The research centre responsible for all the load control research on campus is known as the Centre of New Electricity Studies (CNES), and the central control station is based on the 13th floor of the Engineering Building.

"You can only know what you are able to measure."

Currently the system is able to measure more than 120 electricity consumption points by using 29 installed loggers. The data is measured in real-time and the equipment is capable of uploading the data every half-hour, minute or thirty seconds, depending on the application requirements.

The first phase of the HWLC-system was deployed on two campuses. The main hot water consumers such as hostels and other residences have been selected for control purposes with the possibility of future network extension.

The HWLC-market is mainly dominated by low frequency power line communication devises and radio-controlled units. Various requirements have been set for the University of Pretoria installation in which the radio-controlled devices excelled predominantly. The requirements included:

- Price,
- Speed,
- Features,
- Installation and
- Future network expansion.

Power line communication injectors are used to modulate the control data onto the power lines. The injectors are very expensive and power line communication can only be economically feasible for installations where the injector cost is distributed over large volumes of HWLC-units. The other disadvantage of low frequency power line communication is that only 6-8 commands can be transmitted every half hour in comparison to the radio frequency command ratio of 60 commands per half hour. Both scored equally in terms of installation and future network expansion, but the radio-controlled devices are a step ahead in the features department.

Radio-controlled load switches enable the utility or municipality to uniquely address more than 16 million devices on a single frequency. Switches can also be dynamically classified into specific groups, which enable the load controller to address all the devices contained to the same groups with a single command. Finally, the load controller also has the ability to switch all the devices on a single command, typically used during notch testing.

In summary, the load controller is capable of addressing a switch:

- Uniquely,
- Within group formation or
- As part of the installed fleet every 30 seconds.

Now that the hardware specification is fixed, the next step would be to extract the user information as required by the end user group configuration.

4.1.2 End-User Group Configuration

During July 2000, tests were conducted at CNES to calculate the contribution of in-house residential hot water cylinders relative to the total demand of the University of Pretoria. The study included a total of 16 residences with radio-controlled HWLC-devices already in place. A traditional control procedure was generated to notch all the controllable hot water cylinders simultaneously with the results shown in figure 4.2 and figure 4.3.

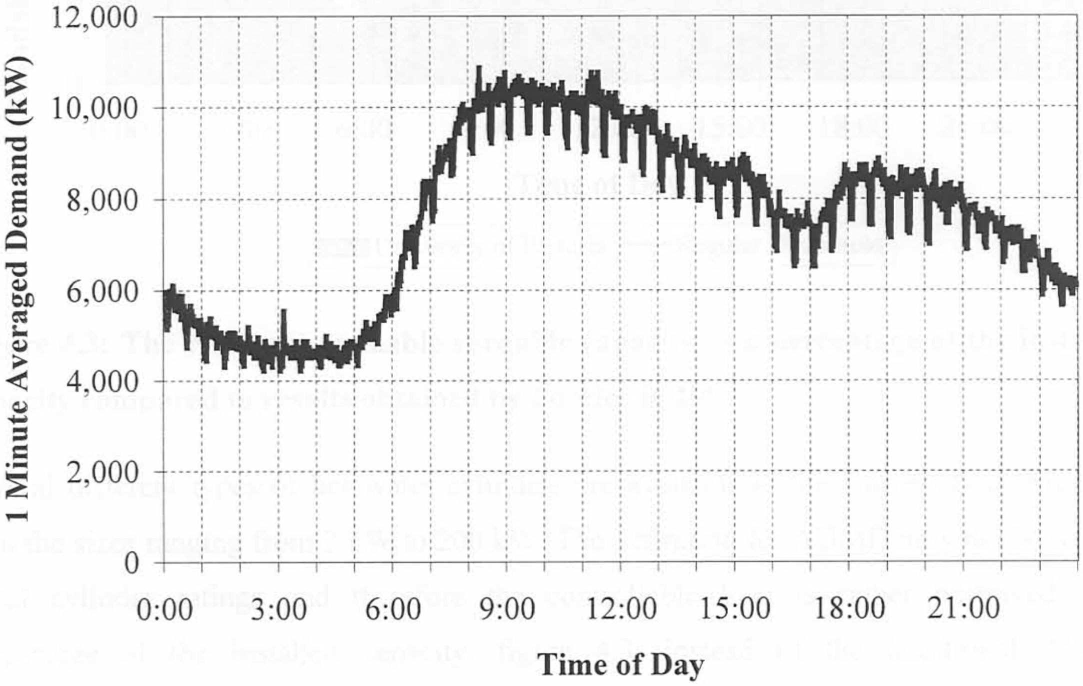


Figure 4.2: University of Pretoria results for notch test conducted on Wednesday, 26 July 2000.

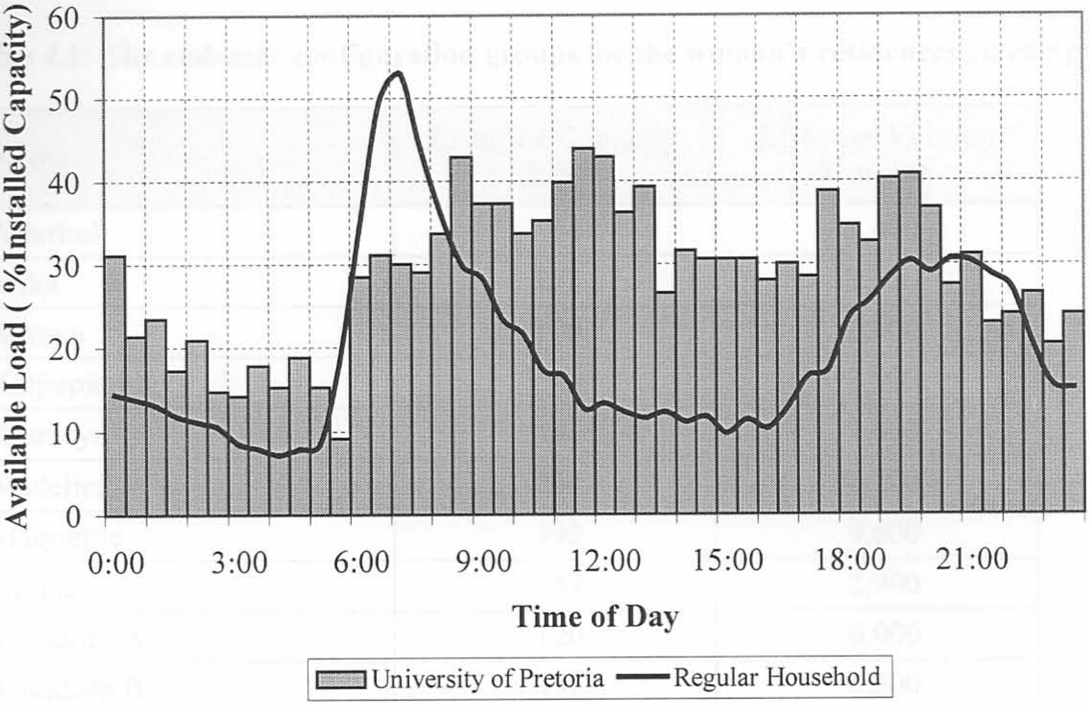


Figure 4.3: The resultant available shedable capacity as a percentage of the installed capacity compared to results obtained by Forelee in 1997.

Several different types of hot water cylinders are available at the University of Pretoria, with the sizes ranging from 3 kW to 200 kW. The definition for ADMD only holds true for equal cylinder ratings and therefore the controllable load is rather portrayed as a percentage of the installed capacity, figure 4.3, instead of the traditional ADMD representation.

The comparative results obtained clearly illustrates that student behaviour is not human at all. The management rules would not necessarily be the same as in a municipal environment but the system is able to contribute savings towards the national peak reduction.

In the past, channel separation tests had to be conducted to determine the contribution of each hostel towards the University of Pretoria load-profile. Nowadays this is no longer required because the consumption of every hostel and residence is measured separately. This, along with the need to disconnect the hot water supply of specific residences during holiday periods, led to the selected group configuration shown in table 4.1 and table 4.2.

Table 4.1: The end-user configuration groups for the woman's residences on campus.

Name	Installed Capacity (kW)	Effective Volume (Litres)
Asterhof	54	3,400
Erika	273	13,650
Jasmyn	130	6,800
Katjiepiering	70	3,900
Klaradyn	138	7,600
Madelief	204	10,200
Magrietjie	192	9,600
Nerina	57	2,900
Tuksdorp A	120	6,000
Tuksdorp B	132	6,600
Totals	1,370	70,650

Table 4.2: The end-user configuration groups for the men's residences on campus.

Name	Installed Capacity (kW)	Effective Volume (Litres)
Boekenhout	152	8,750
Kollege	93	4,900
Maroela	408	20,400
Mopanie	345	17,250
Olienhout	125	7,500
Taaibos	63	3,700
Totals	1,186	62,500

The other difference found through examination of the end-user group configuration notch data was that the men's and woman's residents had a contradictive TADMD shape. The summated result is illustrated in figure 4.4.

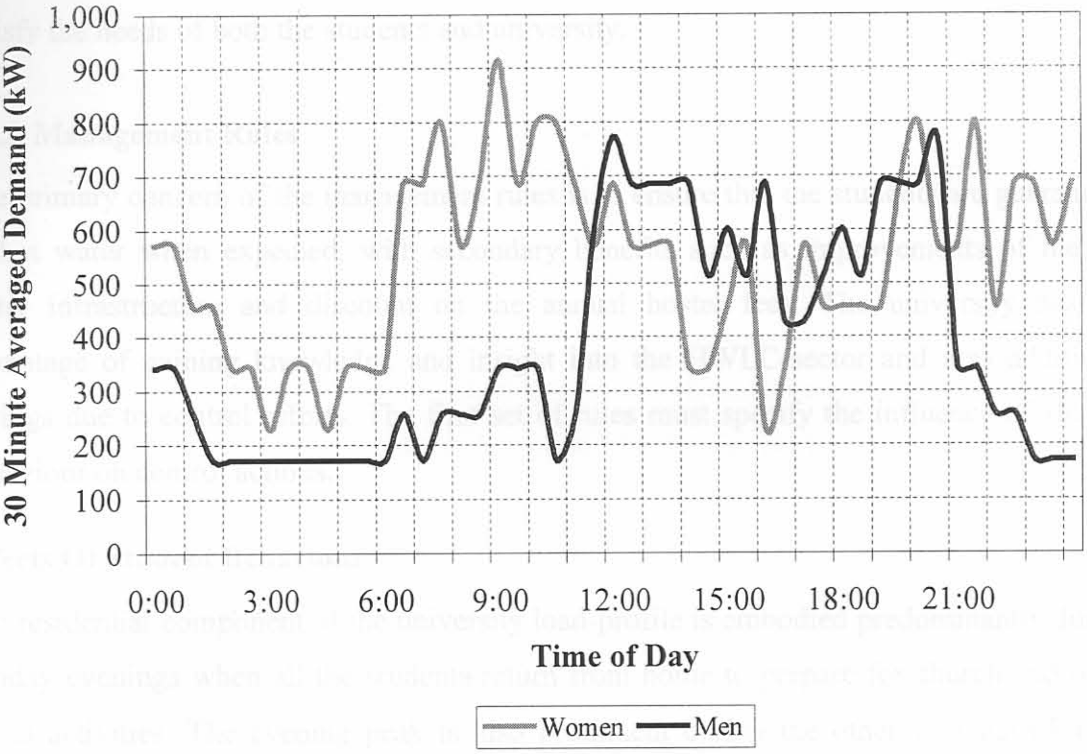


Figure 4.4: TADMD-profiles for July, illustrating the difference in gender consumption patterns.

Continuous notch testing throughout the first operational year ensured that a database of TADMD-profiles for every end-user group was stored. The profiles were recorded on the 15th of each calendar month with a resolution of one-minute integration intervals.

With the manipulation of these results the HWLC-system is now able to:

- ❑ Generate individual footprints for each end user group.
- ❑ Calculate the contribution of each consumer towards the total savings.
- ❑ Accurately simulate load control algorithms for optimisation purposes.
- ❑ Calculate the effect that cold-load pickup will have just before a group is restored, thus acting beforehand to compensate for the expected increase in demand.
- ❑ Predict the set point with much more accuracy.

At this stage enough data is available to formulate a set of management rules that would satisfy the needs of both the students and university.

4.1.3 Management Rules

The primary concern of the management rules is to ensure that the students are guaranteed of hot water when expected, with secondary benefits such as improvements of the hot water infrastructure and discount on the annual hostel fees. The university has the advantage of gaining knowledge and insight into the HWLC-sector and also additional savings due to control efforts. The first set of rules must specify the influence of student behaviour on control actions.

Effects Of Student Behaviour

The residential component of the university load-profile is embodied predominantly during Sunday evenings when all the students return from home to prepare for church and other social activities. The evening peak is also prominent during the other weekdays but all differ in time, depending on the inter-residential activities arranged for that specific day. I.e. Tuesdays are set aside for residential rugby league from 18:00 to 21:00 and Thursdays several internal residential activities occur from 21:00 to 23:00. The student social calendar of each residence, as well as that of the university, must be used to forecast change in behavioural patterns.

Seasonal variations coincides with that found in the domestic sector but special attention must be given to the university holidays. Holidays have a considerable impact in the grid of the University of Pretoria due to the reduction of commercial activities and the change of behaviour of the residential students. In guidance of the work done in section 1.6 (page 15), the effects of different types of holidays or events can be summarised in four categories:

- **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 as depicted by regular Fridays and Mondays.

- ☐ **A Single Holiday That Falls On A Weekday:** A day like this tends to have a minimal load effect on the immediate preceding and subsequent days. The holiday itself can again be estimated as a Sunday.
- ☐ **A School Holiday:** Take the December holiday season as an example. The total energy consumed decreases slightly during exam periods but dramatically decreases at the start of the student's holiday. Work still commences for another two weeks as the lecturers and other administrative personnel fulfil their duties. The demand reaches a minimum during the compulsory closure for the Christmas holiday. The load-profile follows the trend of a regular week with the only difference in the value of the base-load, and only recovers totally in February when all lectural and commercial activities commence.
- ☐ **Special Events:** Special events such as Spring Festival, Intervarsity, RAG, natural disasters, strikes, etc can all have an effect on the university load-profile. For example, the load-profile on the day of Spring Festival follows the shape of a Sunday, but each special event must be taken on it's own credit and handled individually.

The flexibility of the system is extremely useful during holiday periods when residences close down partially. The controller is able to turn of individual cylinders on selected corridors or address the whole residence as a single unit. HWLC-units controlling specific corridors can also temporarily be moved to another group for the duration of the holiday.

Although the effects of student behaviour are known, no formal control strategy has been implemented to accommodate the effects of student behaviour as of yet. The calculations of the set point determines the shedding sequence and therefore are these effects taken into account by calculating and adjusting the shed-level on a daily basis.

Risk Of Cold Water

Pro-active control ensures that the average cylinder temperature does not go below 40°C. This is made possible by simulating the control actions and then adjusting the shed-level until optimal savings without infringement on comfort-levels is guaranteed. Alarms are raised and qualified personnel are notified when any group encounters a possibility of low water temperature levels. The students can also forward any cold-water complaint to a customer care centre, which will be attended to within 24 hours after the complaint has been received.

System Failure

One of the main design parameters of the University of Pretoria HWLC-system was a low failure rate. The real-time consumption is measured on 5 feeders with 3 different sets of measurement options. The three measurement options are then compared to one another and the correct demand value is passed on to the load prediction module. The prediction module then calculates the predicted demand for the half-hour by means of two different algorithms, ensuring sensitivity for all possible load reactions.

With the prediction available, the controller then decides on the best action for the current load control requirement. The group(s) that best suits the action is selected for shedding or restoring and the status of each group is stored with a timestamp in the database for savings calculation and auditing purposes.

A dedicated technical team is also assigned to do scheduled maintenance on a monthly basis. They also functions as a 24-hour unscheduled maintenance response team during critical failures. Analysis of unscheduled maintenance ensures that components are always in stock in case of a critical failure.

4.1.4 Electricity Tariff

The Municipality of Pretoria is the sole supplier of electricity to the university. The main campus and residences are fed from 5 feeders, summated and billed as a single point of supply. The tariff is applied in the form of a demand charge structure and the rates are twofold:

- ❑ The consumed energy costs 9.98c per KWh and
- ❑ The monthly demand charge is fixed at R46.88 per KVA.

The current tariff structure does not promote optimal control on the municipal level for the same reasons as discussed in section 1.8.2 (Incorrect Influence Of Tariff Structure, page 28).

The HWLC-system does not benefit the municipality or even utility at this point in time. The selected control algorithms allow the controller to increase the university's demand during national evening peak times and the university is benefiting from it as well. It must be stated that nothing can be done sustain a win-win situation before another tariff, preferably TOU, is offered to the university.

4.1.5 Required Production Profile

The management rules cover all the required needs of the students to sustain customer-comfort-levels. This paragraph will only be dedicated to production from the university's perspective.

MD control is the only possible savings initiative encouraged by the tariff structure, thus defying the need to shift energy out of the municipal peak times. The management rules allow MD-reduction until risk of cold water comes to play. It is of utmost importance to ensure that management rules relating to customer-comfort have priority over any production requirement.

The average peak demand for the controlled campuses is in the order of 12 MVA, with a total controllable load of about 2.6 MVA. Taking the two-part tariff of R 45.50 / kVA and 9.68c / kWh into account when the HWLC-system was installed, savings accounted to R40,000 or less.

Extensive research was done in the field of hot water dynamics and these findings have been integrated into the expert load control system. As time progressed, smarter features have been implemented into the control algorithm as more information became available. Current savings range between R60,000 and R70,000 per month on a R900,000 electricity bill.

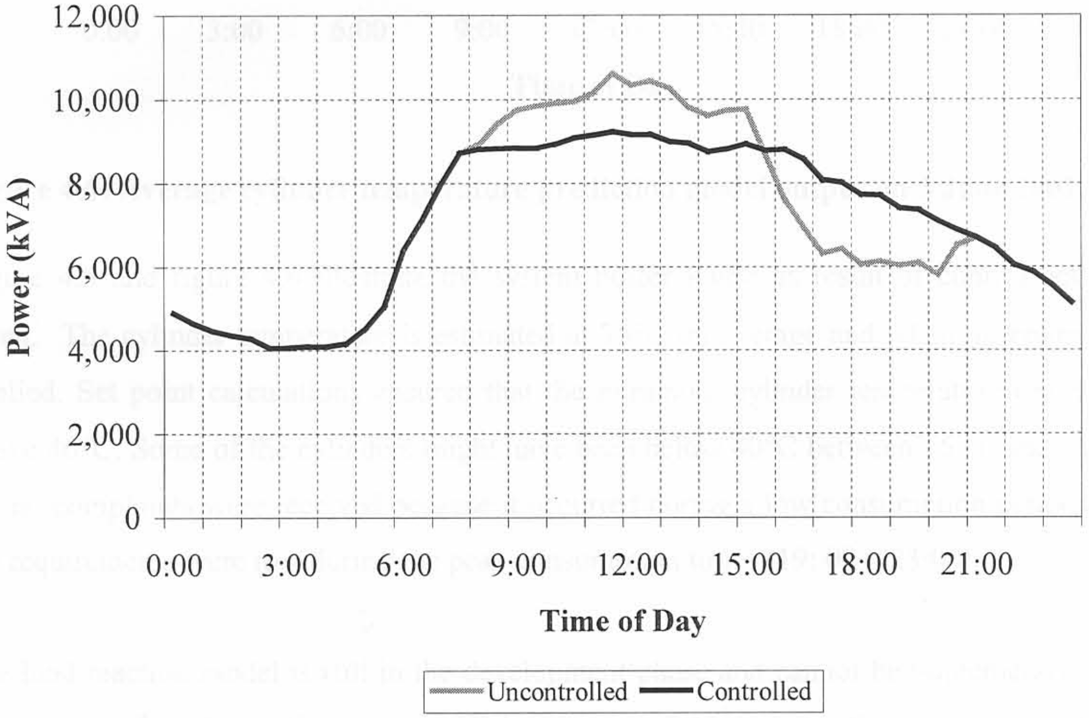


Figure 4.5: Uncontrolled - vs. controlled load-profiles for 5 June 2001.

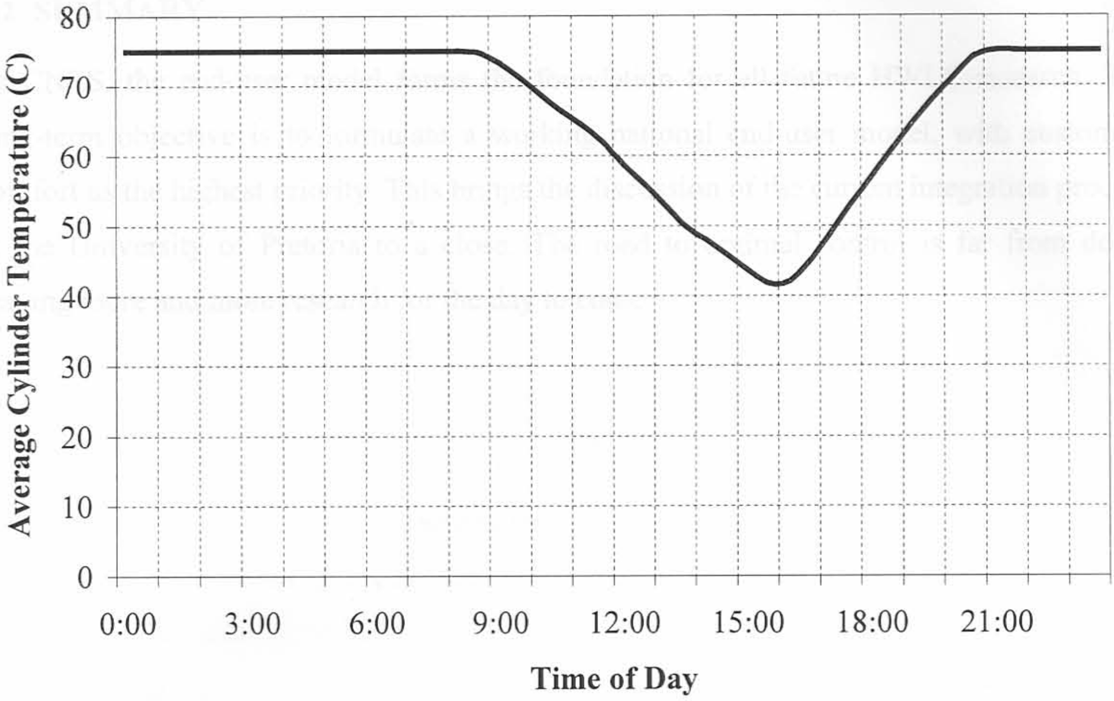


Figure 4.6: Average cylinder temperature prediction model output on 5 June 2001.

Figure 4.5 and figure 4.6 illustrate the system buffer levels as result of control actions taken. The cylinder temperature is estimated at 75°C on average and when no control is applied. Set point calculations ensured that the minimum cylinder temperature remained above 40°C. Some of the cylinders might have been below 40°C between 15:00 and 16:00 but no complaints were received because it occurred during a low consumption period and the requirements were met during the peak consumption times (19: 00 – 23:00).

The load reaction model is still in the development phase and cannot be implemented yet. Some interesting observations came to light in terms of the consumption pattern extraction and will be discussed in the chapter to follow.

4.2 SUMMARY

At CNES, the end-user model forms the foundation for all future HWLC-research. The long-term objective is to formulate a working national end-user model, with customer-comfort as the highest priority. This brings the discussion of the current integration process at the University of Pretoria to a close. The road to optimal control is far from done, leaving more and more research for the day to come.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

This chapter will stimulate the reader to pursue in the field of consumer-orientated control and to expect the unexpected. Utilities and municipalities have dominated HWLC-strategies since infancy. It is inevitable that some emotions would be stirred when the paradigms starts to shift towards consumer-orientated control.

5.1 OVERVIEW

Chapter 1 introduced the reader to the South African electrification crisis and the benchmarks set by Eskom to contain this problem. Various options have been mentioned on both supply and demand-side while the reader was guided to realise the potential of HWLC as energy management solution.

The dog-eat-dog world of today hardly offers any solution without a price. The problems hampering HWLC was not known at the pioneering stages of implementation and it resulted in a negative experience by the general public. Direct - and indirect control strategies have been discussed, which led to the various objectives of the utility, municipality and residential consumer. Unattended effects of human behaviour on the national load-profile were examined to facilitate the possible pitfall areas and to find a sphere of mutual satisfaction.

The final segment of chapter 1 was dedicated to work done in the field of HWLC-system dynamics. Imperative trends such as cold-load pickup and load restoration were discussed, based on the work done by other researchers in the field. The discussion flowed into incorrect application of various tariff structures and other deficiencies encountered by existing HWLC-systems.

From there on it was possible to define an HWLC-methodology, only applicable for optimal load control on a national level. A micro level model was derived to pursue national savings on municipal level. Global compatibility constrained the model definition, which made it impossible to define the inputs to the bone. System details are unique to each control system and can be dealt with during the implementation phase.

Model inputs are therefore not system specific and defined as the:

- ☐ End-user group configuration,
- ☐ Electricity tariff,
- ☐ Required production profile,
- ☐ System & process limitations and constraints,
- ☐ Management rules and
- ☐ Buffer systems.

The processed inputs resulted in the following measurable outputs:

- ☐ Electricity load-profiles and
- ☐ Buffer system-levels.

Specific problem areas identified during the model description included:

- ☐ Cold-load pickup,
- ☐ Pro-active control,
- ☐ Consumer group configuration,
- ☐ Minimise risk of cold water and
- ☐ Savings distribution.

A methodology for each problem was formulated with the intention of directing the correct application within the end-user model. Two methodologies required specialised mathematical procedures to prepare the model-input-data.

Chapter 3 was dedicated to develop the load reaction - and the temperature prediction models.

Finally Chapter 4 painted the picture of load control on campus. The University of Pretoria can be seen as a pioneer for new ventures in HWLC, but experience in the field had a price tag attached to it.

5.2 CONCLUSIONS AND RECOMMENDATIONS

This dissertation will not necessarily convince every municipality to alter their load control strategies, but the defined methodologies can be used as the foundation for future development. This section carries the conclusions and recommendations made by the author in respect of the work done to date.

5.2.1 End-User Model

The end-user model was developed as a guide to integrate consumer friendly HWLC into new - or existing HWLC-systems, leaving enough freedom for system specific criteria. Chapter 4 used the University of Pretoria as example to illustrate the process of filling the skeleton model with flesh according to user – and system specifications. The end-user model can be applied to any HWLC-system, controlled by utility or municipality, as long as the system specific objectives set by the utility, municipality and residential consumers are met.

The management rules can only be defined once the specific needs of the residential consumers have been determined and can easily be revealed by creative market research activities. Consumer needs will vary between:

- ❑ High - and low income groups,
- ❑ Costal - and inland provinces,
- ❑ Rural - and urban municipalities, etc.

HWLC-systems can only be as successful as the accuracy of its consumer group configuration. The next paragraph will take a closer look at the advantages of dividing users into groups according to their hot water requirements.

5.2.2 Consumer Group Configuration

Research has shown that most of the HWLC-systems in South Africa use a random consumer distribution technique. This means that the population of a specific user group is randomly scattered across the entire controllable region and all the user groups contains the same amount of members. The reasons for this is to:

- ☐ Distribute the load reaction over all the transformers and switchgear when a specific group is restored,
- ☐ To cancel the behavioural differences out between various residential areas and
- ☐ It is easier to calculate the savings when all the user groups have the same installed capacity.

At the time when these systems were developed, the random distribution technique was almost unbeatable. Today's computer technology allows researchers and programmers to implement complex algorithms into the control strategies. It is possible to divide the users into smaller user groups and to calculate their individual contribution in terms of utility bill reductions.

"You cannot measure without influencing the results."

The traditional form of notch testing involves switching all the devices OFF on the half-hour for five minutes, switching them back ON afterwards. The five-minute shedding interval has a significant CLP effect on the data, affecting the resultant ADMD values. Thanks to the increased data delivery rate of radio-controlled units, the notch interval period can be decreased to 30-seconds. CNES is currently conducting tests to determine the optimal notch interval length, minimising the CLP effect and still be able to measure the notch value, and the optimum period between notches. The outcome of these experiments will minimise the measurement uncertainty and result in more accurate consumer consumption profiles.

The consumer group configuration proposal on page 41 allows the user to specify the time during the day in which he wishes to extract hot water from the cylinder. Stated from another perspective, the user can select specific periods in the day that the controller may extract energy below the 40°C threshold. This group distribution strategy allows the HWLC-system to extract the optimal amount of energy from each hot water cylinder, without infringing on comfort-levels.

The proposed consumer groups are only a guideline and consumption can primarily be categorised into four time intervals:

- ☐ Morning (6:00 – 10:00),
- ☐ Midday (10:00 – 18:00),
- ☐ Sundown (18:00 – 20:00) and
- ☐ Evening (20:00 – 6:00).

These intervals coincide with the national peak times and will be complemented when controlled according to a TOU-tariff. The categorisation of users into specific consumption intervals will refine the accuracy of the load reaction model, the average cylinder temperature model as well as the savings distribution. This can be illustrated by taking another look at the ADMD profile of South Africa.

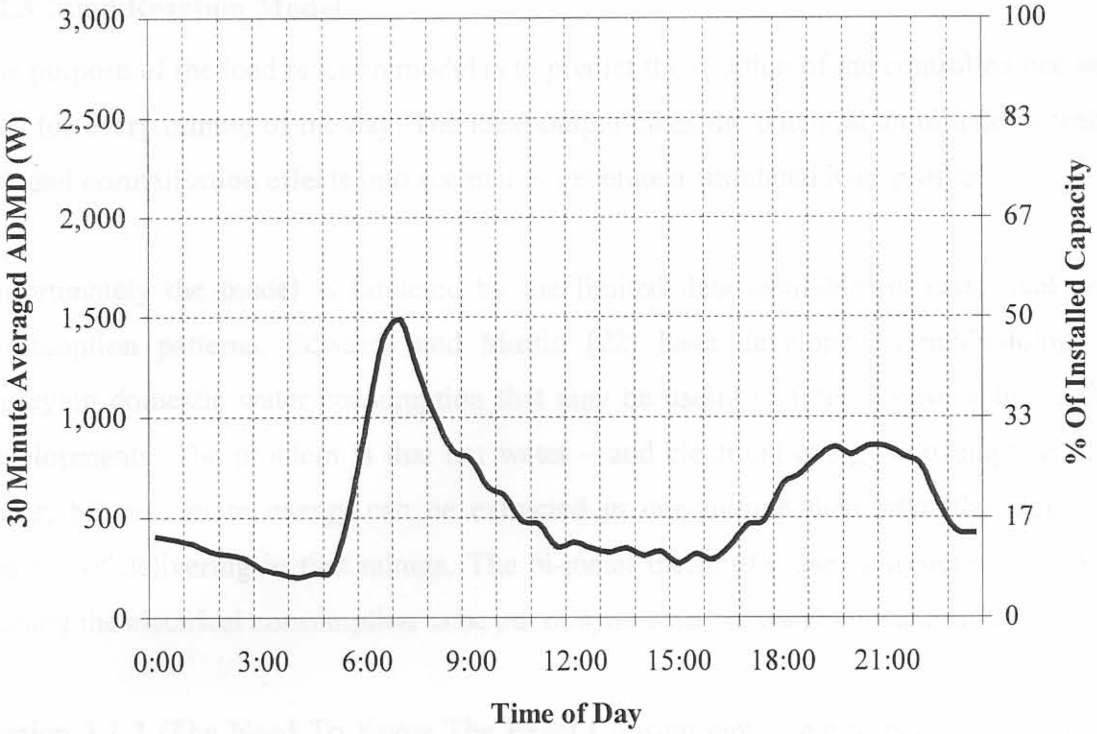


Figure 5.1: South African winter ADMD and percentage profile.

Not all of the residential consumers require hot water at the same time. The peak consumption occurs between 7:00 and 8:00 during no-control conditions, and only 50% of the installed capacity is utilised. Let's use the example again where the total population size of controllable cylinders is equal to 9,000 units. Assume that 3,500 cylinders will never consume hot water during the morning interval. The result is that the net population of hot water cylinders is equal to 5,500 cylinders between 6:00 and 10:00 in the morning.

In this example when shedding occurs from 6:00 to 10:00:

- The load reaction model will clip the $LR_{\text{Higer Boundary}}$ at 16,500 instead of 27,000 kW,
- The decreased value of the water mass used in the average temperature model will give a more realistic value of the cylinder temperature, and
- Only the users that contributed to the savings for this period have to be compensated.

The specific details of the influence of the consumer group configuration on these models will be discussed in the subsequent paragraphs.

5.2.3 Load Reaction Model

The purpose of the load reaction model is to predict the reaction of the controlled hot water load for every minute of the day. The ideal output takes the potential amplitude as well as the load normalisation effects into account to generate a simulated load-profile.

Unfortunately the model is hindered by the limited data available on residential water consumption patterns. Edwards and Martin [22] have developed a methodology for surveying domestic water consumption that may be useful in future consumption pattern developments. The problem is that hot water – and electrical energy consumption is not linear, because more energy can be extracted in one minute than what the element is capable of delivering in that minute. The bi-metal thermostat uses a hysteresis set point, causing the electrical consumption to be out of sync with the water consumption.

Section 3.1.2 (The Need To Know The Exact Consumption Pattern, page 66) has shown that the TADMD on its own is does not supply enough information for predicting the exact hot water load reaction but it is possible to say that:

- The CLP is only a function of the amount of cylinders that would have consumed energy during T_{Shed} and
- The load normalisation curve can be constructed by using the calculated CLP, the amount of energy extracted during T_{Shed} and the real-time consumption during normalisation.

These results can also be verified with a real-life example by using the August 1999 test results described in section 3.1.6 on page 82. This time the profile of the Emergency Interrupt Test (Wednesday) is compared to that of the Wholesale Electricity Test (Friday).

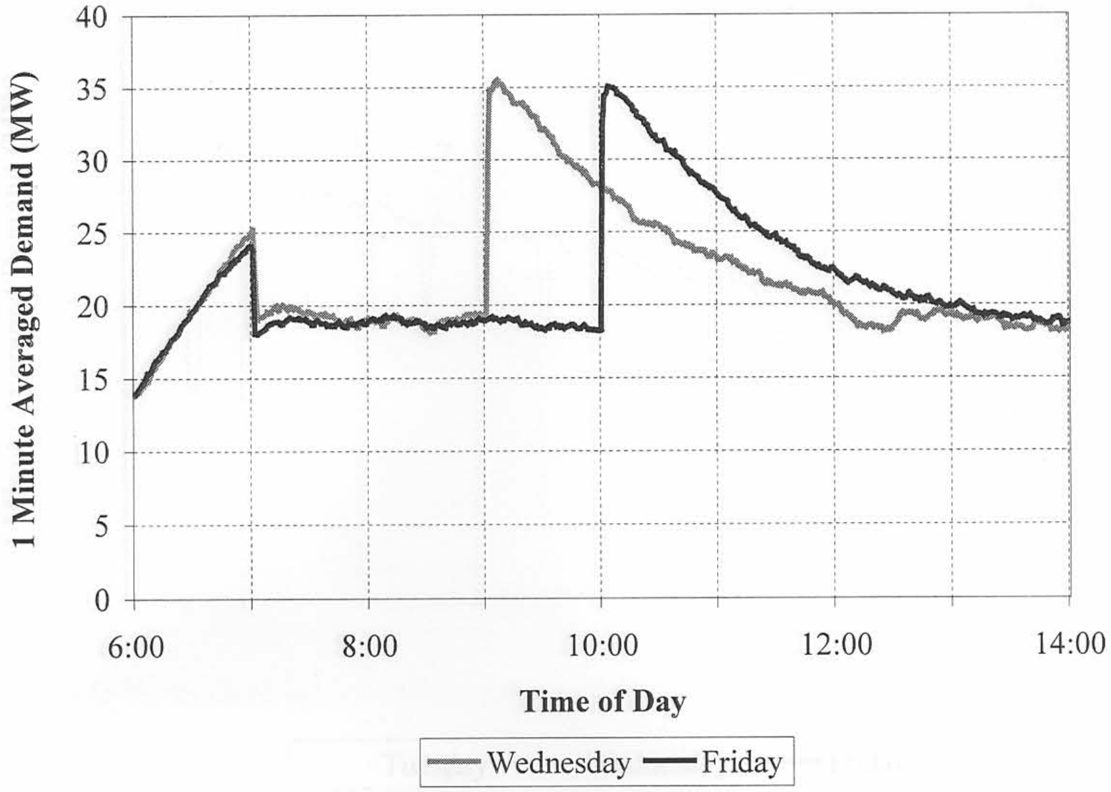


Figure 5.2: August 1999 municipal load curtailment tests.

At first sight, the results in figure 5.2 are rather surprising. The Friday load was restored at 10:00, an hour later than on Tuesday, with almost equal potential amplitude values. The load reaction value in both tests are equal because the amount of consumers that required hot water was the same for both these days. The CLP value is therefore not a function of the shedding period length, but indeed a function of the morning consumer group population.

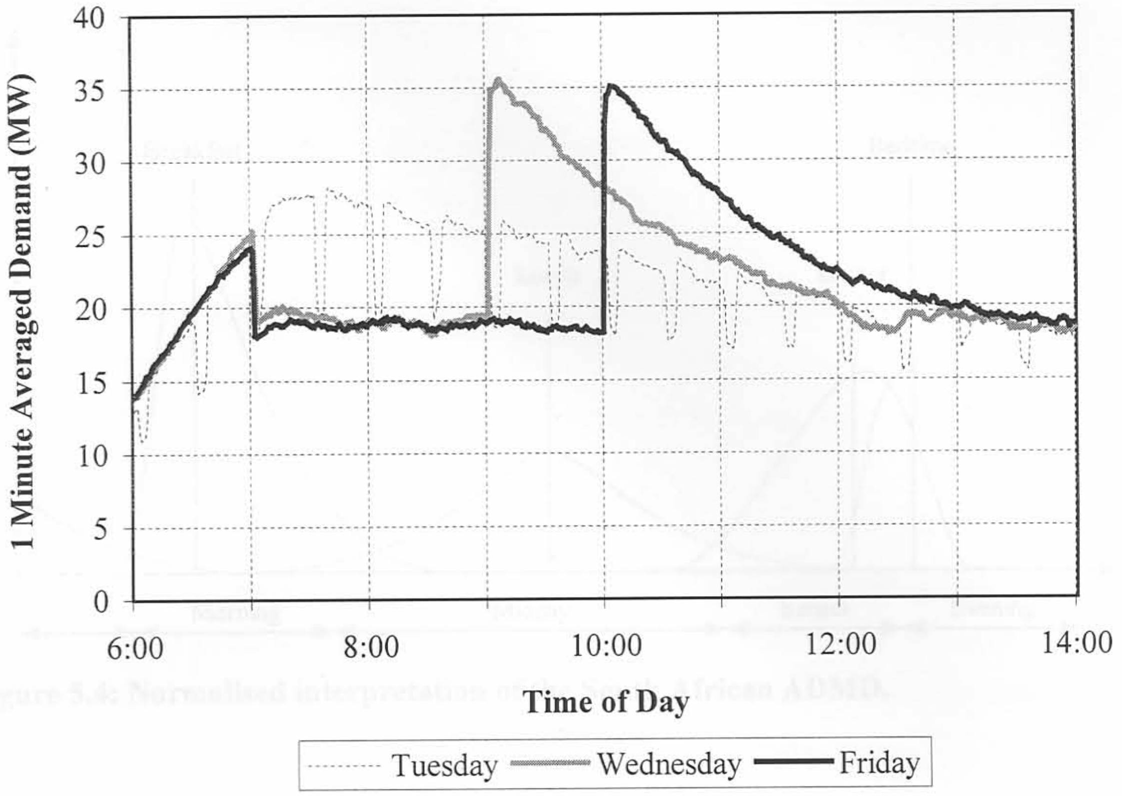


Figure 5.3: Difference in the load normalisation.

Figure 5.3 was generated to illustrate the differences in the load normalisation of the two days and to verify that the load normalisation postulate is true. The morning consumer group population fixed the CLP values at 35 MW and the extracted energy is replaced immediately after the load has been restored. The load normalisation took 180 minutes (10:00 – 13:00) during the Friday test in comparison to the 155 minutes (9:00 – 11:35) on Tuesday. The only differences between these profiles are:

- ☐ The amount of extracted energy that has to be replaced and
- ☐ The real-time consumption value at the restoration time.

These results conclusively prove that the neither the potential amplitude, nor the load reaction curves are necessarily exponential, as initially stated by Calmeyer [17]. The exponential curves extracted on system level are a result of the normal distribution found in large populations. Each time interval specified on page 117 has its own normal distribution based upon a specific human behavioural activity, and is illustrated in figure 5.4.

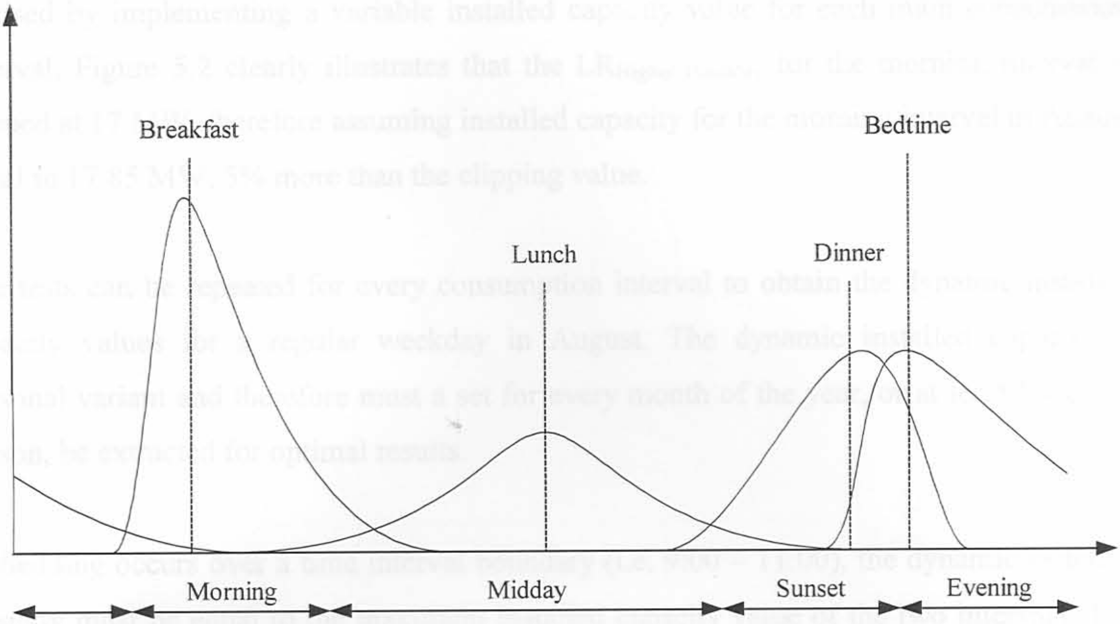


Figure 5.4: Normalised interpretation of the South African ADMD.

Say for instance the load in figure 5.3 is not restored at all. The potential amplitude will remain constant until new members from the midday interval start to consume hot water. The potential amplitude will increase as the members of the midday interval request to consume energy, with the growth decreasing after lunch. This process will repeat itself within the remaining peak consumption periods until all of the hot water cylinders have requested energy at some point or another. Clipping of the potential amplitude will occur at the installed capacity value.

Calmeyer was correct to say that the potential amplitude was limited by the installed capacity, but the growth does not occur within a single exponential stage

The load reaction model can only rise to the occasion once it is possible to estimate or measure the electrical consumption patterns of individual hot water cylinders. For the time being, the load reaction boundaries can be used to assist pro-active load control.

The improvement of the $\text{LR}_{\text{Higher Bounday}}$ prediction, mentioned in section 5.2.2, can be realised by implementing a variable installed capacity value for each main consumption interval. Figure 5.2 clearly illustrates that the $\text{LR}_{\text{Higher Bounday}}$ for the morning interval is clipped at 17 MW, therefore assuming installed capacity for the morning interval in August equal to 17.85 MW, 5% more than the clipping value.

The tests can be repeated for every consumption interval to obtain the dynamic installed capacity values for a regular weekday in August. The dynamic installed capacity is seasonal variant and therefore must a set for every month of the year, or at least for every season, be extracted for optimal results.

If shedding occurs over a time interval boundary (i.e. 9:00 – 11:00), the dynamic installed capacity must be equal to the maximum installed capacity value of the two intervals. The dynamic installed capacity will also increase the accuracy of the average temperature prediction model and will be discussed in the following paragraph.

5.2.4 Average Cylinder Temperature Model

There is always risk of cold water present during any load control action. The average temperature of a group can be equal to 55°C, but the deviation within the group could cause the minimum temperature to be less than 40°C. The classification of users into similar usage patterns, along with the variable installed capacity proposal, will ensure that the deviation around the mean temperature value decreases as illustrated in figure 5.5.

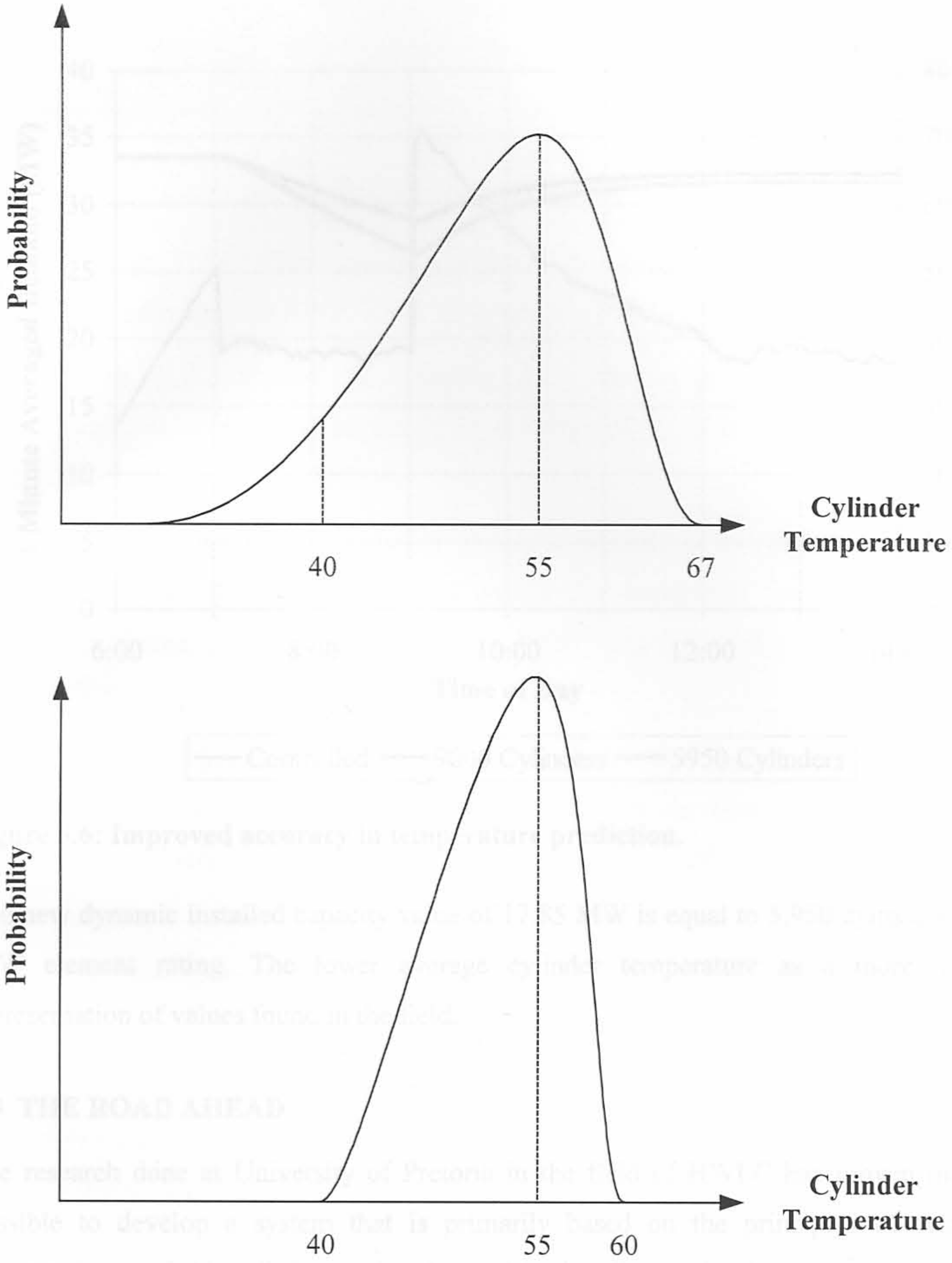


Figure 5.5: Desired effect of consumer group configuration on the average cylinder temperature.

Even with the proposed improvements, the entire user group still stand a chance of experiencing cold water, but the individual cold water complaints will definitely be less. Figure 5.6 depicts results after the implementation of the dynamic installed capacity proposal.

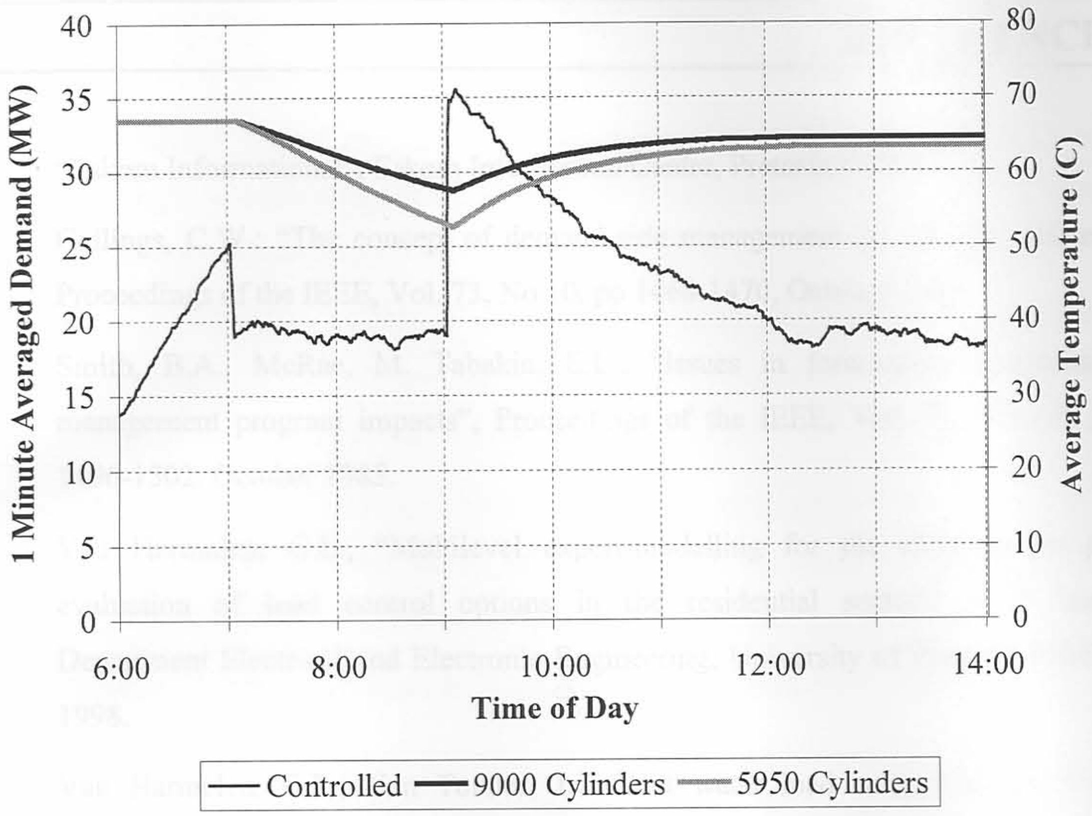


Figure 5.6: Improved accuracy in temperature prediction.

The new dynamic installed capacity value of 17.85 MW is equal to 5,950 cylinders with a 3kW element rating. The lower average cylinder temperature as a more accurate representation of values found in the field.

5.3 THE ROAD AHEAD

The research done at University of Pretoria in the field of HWLC has proven that it is possible to develop a system that is primarily based on the principles of customer-orientated control. Not all the results obtained in this dissertation have been implemented yet, but various motivations helped to reserve more funds for future development. It won't be long before the hot water consumption patterns can be derived on device level.

"The road to optimal control is a brutal one but a dense forest has many fruit."

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