OPTIMIZATION OF THE IN-LINE SANITARY WATER HEATING SYSTEM FOR DEMAND SIDE MANAGEMENT IN THE SOUTH AFRICAN COMMERCIAL AND INDUSTRIAL SECTORS

BY

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ABSTRACT

It is currently estimated that South Africa will be running out of surplus electrical capacity by the year 2007. This estimate is based on the current growth in economy that primarily includes the electrification of half-a-million new households per year, with a final target of 5 Million households by 2007. This situation is forcing ESKOM to take action to reduce peak electrical demand by initiatives such as the implementation of Demand Side Management (DSM) programs. These DSM programs are currently aimed at the industrial and commercial sectors where bigger impacts in load shifting can be achieved than in the residential sector, which is the actual cause of the surplus capacity run-out. The reason for this is that the large amount of individual consumers in the residential sector presents several barriers to the implementation of DSM programs in this sector.

This study addresses the optimisation of sanitary water heating systems in the commercial and industrial sectors, for DSM purposes. Commercial and industrial applications are considered separately, since a difference in application strategy emanates from the different tariff structures utilized in the industrial and commercial sectors. In the industrial sector where the focus lies on load shifting, an in-line electrical resistance heater will be utilized. In the commercial sector where the focus lies on both load shifting and energy efficiency, a combination of heat pumps and in-line electrical resistance heaters will be used. In both applications the heating equipment is connected in the so-called 'improved in-line heating' configuration developed in previous studies.

The first part of the study provides results obtained from sanitary water heating DSM projects that were completed at several commercial and industrial sites. Firstly new hot water consumption patterns for hotels and mine residences are provided. The differences between these profiles, and those found in previous studies for the residential sector, were highlighted. This was achieved by a simulation study, which resulted in a design envelope for the most important system specifications, for different hot water consumption profiles.

Results for in-line heat pump water heating systems installed in commercial buildings were then provided. These results show that direct benefits for both utility and building owner can be achieved in terms of peak demand reduction. Additional benefits are also obtained by the building owner in terms of energy efficiency improvements due to the utilisation of the heat pump unit.

Results for a utility funded DSM project to install in-line water heating systems at several mine residences were then provided. A significant DSM load shift was achieved by this project, to the benefit of ESKOM. The results showed how the in-line heating systems enabled load shifting out of utility critical periods without any loss in hot water availability to system users.

Part two of the study provides results of optimisation studies for sanitary water heating system design in both commercial and industrial sectors. This is achieved by first of all developing a water-heating system simulation program based on simplified first law analysis. This model successfully demonstrated a high level of accuracy for both electrical demand and thermal availability prediction, for different configurations of sanitary water heating systems. Simulation results were verified with measured results obtained from the commercial building and mine residence projects as provided in part one of this study.

The new simulation program, together with the new hot water consumption patterns for hotels, was then used in an optimisation study for commercial building water heating systems. The study provided optimal heating and storage capacities for a broad range of system parameters. The most optimal solution for designing a completely new water heating system was also provided. The study also showed that additional control upgrades resulted in improved cost- and energy efficiency for the system. Favourable economic returns are obtained by the proposed retrofits; an Internal Rate of Return of at least 47.1% is achieved for the different tariff structures employed in the commercial sector.

Finally, a digital control algorithm was developed that optimises operational cost efficiency for sanitary water heating systems in the industrial sector, subject to Real Time Pricing (RTP). The study showed that significant savings are possible; a theoretical operational cost reduction of 20%-29% can be achieved at the case study plants. Cost reductions are mainly a function of system utilization: bigger non-dimensional heating and storage capacities result in higher savings potential.

The optimisation studies done in this thesis provide 'real world' solutions with a well balanced trade-off between simplicity and efficiency. Well-evaluated options for DSM programs in the different sectors are therefore presented, which can obtain benefits for both electrical utility and client. These options should therefore be able to boost the viability of sanitary water heating system DSM projects in the South African Energy Services Industry.

TITEL: OPTIMERING VAN DIE INLYN WATER VERHITTINGS STELSEL VIR AANVRAAGKANT BESTUUR IN SUID AFRIKA SE KOMMERSIëLE EN INDUSTRIëLE SEKTORE

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UITTREKSEL

Volgens onlangse vooruitskattings kan Suid Afrika teen die jaar 2007 'n tekort aan surplus elektriese kapasiteit ontwikkel. Hierdie vooruitskattings is gebaseer op die huidige groei in die ekonomie, wat hoofsaaklik die elektrifisering van 500 000 nuwe huise per jaar insluit. Hierdie program vereis dat 5 Miljoen huise teen 2007 gebou en ge-elektrifiseer sal wees. Die situasie dwing ESKOM om programme te implementeer wat elektriese pieklas vermindering kan lewer. Huidiglik word gefokus op projekte in die kommersiële en industriële sektore, waar groter pieklas verminderings 'per kliënt' moontlik is.

Hierdie studie fokus op die optimering van warmwater stelsels vir kommersiële geboue en industriële woonareas. Aparte optimering studies word vereis weens die verskille in elektriese tariefstrukture wat in die onderskeie sektore gebruik word. In die industriële sektor word slegs elektriese weerstands verhitters gebruik, aangesien die tariefstruktuur slegs lasskuiwing na goedkoper tye van die dag aanmoedig. In kommersiële geboue moedig die tariefstruktuur ook 'n vermindering in elektrisiteits verbruik aan. Dus word daar hittepompe tesame met elektriese verhitters geinstalleer om sodoende energie effektiwiteit te verbeter. In beide gevalle word die verhitters in die sogenaamde 'verbeterde in-lyn verhitting' konfigurasie gekoppel wat in vorige studies ontwikkel is.

Die eerste deel van die studie bestaan uit gemete resultate en besprekings van verskeie warmwater stelsel projekte wat in die kommersiële en industriële sektore gedoen is. Eerstens word nuwe warmwater verbruik profiele vir hotelle en sentrale woonareas in die mynbou bedryf verskaf. Sekere verskille word uitgelig tussen hierdie nuwe profiele, en profiele wat in vorige studies voorsien is. 'n Simulasie model word gebruik om die invloed van hierdie verskille op ontwerp spesifikasies te illustreer.

Resultate van verskeie hitte pomp stelsels wat in hotelle geinstalleer is word bespreek. Die resultate toon dat direkte voordeel uit 'n installasie verkry word deur beide die elektrisiteits voorsiener en die gebou eienaar as gevolg van die verlaging in pieklas bydrae van die warmwater stelsel. Die gebou eienaar trek ook addisionele voordeel uit die verbeterde energie effektiwiteit van die hitte pomp stelsel.

Resultate word getoon vir 'n ESKOM gesubsidieerde projek om Aanvraagkant Bestuur te implementeer in die industriële sektor. 34 inlynverhitterstelsels is gedurende die projek geinstalleer by verskeie warmwater stelsels in mynhostels. Die resultate toon dat die inlynverhitterstelsels dit moontlik maak om elektriese las uit ESKOM se kritieke pieklas periodes te skuif, sonder enige verlies aan warmwater beskikbaarheid vir die gebruikers.

Die tweede deel van die studie voorsien resultate van optimering studies vir warmwater stelsel ontwerp in die kommersiële en industriële sektore. Die optimeringstudies word moontlik gemaak deur eerstens 'n nuwe simulasie model vir warmwater stelsels te ontwikkel. Die model lewer akkurate resultate wanneer die werking van verskillende tipes warmwater stelsels gesimuleer word. Resultate is geverifieer met metings wat verkry is vanaf die kommersiële en industriële projekte wat in die eerste deel van die studie voorsien is.

Die simulasie program tesame met die nuwe warmwater verbruik profiele word nou gebruik in 'n optimeringstudie vir warmwater stelsels in kommersiële geboue. Optimale verhittings- en stoor kapasiteite word voorsien vir 'n verskeidenheid van stelsel grootte kombinasies. Die mees optimale kombinasie vir verhitting- en stoorkapasiteit word ook voorsien sou 'n nuwe stelsel ontwerp word. Die studie bewys dat addisionele beheer algoritmes die ekonomiese lewensvatbaarheid van die warmwater stelsels verder kan verhoog. Interne opbrengs koerse van 47.1% en hoër word verkry vir die verskillende tariewe wat in die kommersiele sektor gebruik word.

Laastens word 'n digitale beheer algoritme ontwikkel, wat die koste effektiwiteit van warmwater stelsels in die industriële sektor verhoog. Die studie bewys dat beduidende besparing verkry kan word vir warmwater stelsels, gebaseer op 'n 'intyds-geprysde' tarief. Teoretiese koste besparings van 20% tot 29% is moontlik. Besparings potensiaal is 'n funksie van stelsel gebruik; hoër besparings word verkry vir stelsels met groter nie-dimensionele verhittings en stoor kapasiteite.

Die optimeringstudies in hierdie tesis voorsien realisties uitvoerbare en goed ge-evalueerde keuses vir Aanvraagkant Bestuur in beide sektore. Die voordele wat hieruit geput kan word, geld vir beide elektrisiteit voorsiener en kliënt. Die studie kan dus die lewensvatbaarheid van projekte in Suid Afrika se Energie Industrie verhoog.

NOMENCLATURE

English Symbols

C_p	Specific heat at constant pressure
K_{loss}	Heat loss factor
$\dot{m}$	Mass flow
$\dot{Q}$	Volume flow
C	Overhead costs
F	Energy consumption
n	number of (years, time steps etc)
P	Power (heating demand)
E	Energy content
$\dot{E}$	Rate of energy change
S	Annual savings
T	Temperature in degrees Celsius (°C)
V	Volume
T^*	Non-dimensional temperature
T^*_{set}	Non-dimensional set-point temperature
Q^*	Non-dimensional heating capacity
V^*	Non-dimensional storage capacity
h^*	Non-dimensional height

Greek Symbols

ρ	rho (Density)
Δ	Delta (Difference)
$\sum$	Sigma (Sum of)

ABBREVIATIONS

COP	Coefficient of Performance
DHS	Default Heating Schedule
DSM	Demand Side Management
ESKOM	South African Electrical Supply Utility
IC	Intervention Control
IRR	Internal Rate of Return
MD	Maximum Demand
RTP	Real Time Pricing
TOU	Time-of-use

PERMISSION OBTAINED FROM CO-AUTHORS OF PUBLICIZED JOURNAL ARTICLES TO USE ARTICLE CONTENT IN THESIS

A part of Chapter 3 of this thesis has been published in 2002 in the International Energy Efficiency in Commercial Building Conference proceedings, where the author presented the work. It was also published in 2004 as a full-length article in the international journal *Energy Conversion and Management (Elsevier).* Chapter 2 of this thesis has been published in 2005 as a full-length journal article, also in *Energy Conversion and Management* journal.

The article: *Demand Side Management for Commercial Buildings using an In-line Heat Pump Water Heating Concept,* was co-authored by Prof Dr. PG Rousseau and Mr. Martin van Eldik.

- Prof Rousseau was the project leader in the actual implementation project that led to the article content. His contributions to the article were; a) initial structuring of the article, b) overseeing the write-up process and c) final review of the written work.
- Mr. Van Eldik was the project engineer responsible for the design and manufacturing of the heat pump units used in the project that led to the article content. His contribution to the article was to assist in the write-up process and final review of the article.

The article: *Sanitary hot water consumption patterns in commercial and industrial sectors in South Africa: Impact on heating system design,* was co-authored by Prof Dr. PG Rousseau.

Prof Rousseau was the project leader in the actual implementation project that led to the article content. His contribution was to oversee the write-up process and final review of the written work.

Both co-authors have given their permission that the work published in both articles be used in the thesis.

Prof. Dr. PG Rousseau

Mr. M Van Eldik

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CHAPTER 1 – INTRODUCTION

Abstract

This study emanates from the need for the implementation of Demand Side Management programs in the South African commercial and industrial sectors. According to the most recent National Energy Regulator (NER 2003) Policy discussion document, it is estimated that South Africa will run out of peak electrical generating capacity within the next few years. This will either require new generation capacity to be built as the electrical demand increases among various customers in the South African economy, or the implementation of Demand Side Management programs to reduce load contributions in peak demand periods. This chapter summarizes the need for Demand Side Management in South Africa, as well as the barriers that need to be overcome to successfully implement these programs. The chapter further provides a summary of the most important literature survey findings of each of the subsequent chapters in the study, the objectives of each chapter, as well as the major contributions made by this study as a whole.

1 Background

1.1 The need for Demand Side Management in South Africa

Demand Side Management (DSM) programs hold enormous potential throughout the world in industrialized countries. Various scenarios are however present in different parts of the world regarding the level of DSM practices. In the USA for instance, a deregulated market for generation services exist, with several vertically integrated utilities having an interest in selling more energy at higher prices. DSM programs that reduce consumption may place downward pressure on these energy prices. For this reason there has been a downward trend in the implementation of DSM programs in the USA (Boyle (1996), US DOE EIA (1997)). In contrast to the USA, some of the utilities in European countries such as France, Greece and Ireland are state-owned with regulatory oversight, while others such as the United Kingdom have privately owned utilities. DSM is being applied in Europe for a variety of reasons, such as environmental concerns, transmission and distribution deficiencies, or peak load problems. Looking at DSM programs in the global context, it is clear that each country has its own reasons for implementing DSM or not, whether it is utility regulator enforced, or driven by pressures from trade unions or consumers (Boyle (1996)).

A unique set of reasons for implementing DSM also exists in South Africa. The South African utility, ESKOM, generates one half of the continent of Africa's total electrical output (Etzinger (1995)), with South Africa consuming more than 80% of the ESKOM generated load. The country has an extremely energy intensive economy with a high dependence on the mining and base metal industries. These large-scale industries consume considerable quantities of electrical energy, but the daily demand profile is reasonably constant throughout the day with very few peak periods. The same cannot be said for the residential sector. A profile with very prominent morning and evening peaks has existed in the residential sector since the 1980's up to the mid 1990's, but this has provided no problems for South Africa's installed base-load coal fired generation plants. The country is however in the process of electrification of 450000 - 500000 households per year as part of the government's Reconstruction and Development Program (RDP), with a final target of 5 Million household by 2007 (Africa (2003)). The demand profile of the residential sector is therefore becoming increasingly 'peaky'. This is illustrated by the fact that the residential peak demand currently contributes more than 30% of the national maximum demand, but energy consumption is less than 20% of the national total. (Matlala (2004)). This situation has recently reached a critical level. On 15 July 2004 for instance, a new peak demand record in excess of 34000 MW was recorded between 18:00-19:00.

Given this, the National Energy Regulator estimates that ESKOM will run out of surplus capacity by 2007. The implementation of utility funded DSM programs, combined with existing load management programs are therefore of utmost importance to avoid capacity run-out for ESKOM. Since the residential sector load is made up of a very large number of individual consumers, it is difficult to implement DSM programs in this sector (Den Heijer (2005), Africa (2003)). Therefore, DSM programs are currently aimed at the industrial and commercial sectors where bigger impacts in load shifting can be achieved. The daily period currently targeted by utility funded DSM projects is 18:00-20:00, where the national load profile shows the most prominent demand peak.

1.2 DSM versus expansion of generating capacity

Demand Side Management programs hold a significant advantage in a number of areas over the expansion of generation capacity. Firstly, it can provide a solution to peak electrical capacity problems within a relatively short period. The National Energy Regulator (NER 2003) estimates that the yearly implementation of DSM projects can shift 180 MW during peak demand periods between 18:00-20:00 on weekdays. This figure represents the target for every year of DSM implementation, with a final target of 1600 MW by 2015 (Africa (2003)). To generate additional electrical capacity requires the construction of new power stations, and this will take an extensive period, whether it is coal-fired, nuclear or hydro plants. Secondly, the projected cost per MW shifted by implementing DSM programs is less than 45% of the cost per MW of constructing a power station (Africa (2003)). Thirdly, a power station with a typical life cycle of 25 years only recovers its implementation cost well into the second half of its life cycle, at 90% grid availability (Etzinger (1995)). This implies that if a power station is only constructed to supply power during peak demand periods, the utility will probably show a negative rate of return for that power station over the whole of its life cycle.

1.3 Implementation strategies for DSM programs

The successful implementation of any utility funded DSM program requires an agreement between utility, Energy Services Company (ESCO) and client. The client in this case is the owner of a large commercial- or industrial sector facility that consumes significant quantities of energy in peak demand periods. The ESCO proposes the removal of a certain amount of energy consumption out of the DSM peak periods to the utility, but both utility and client must benefit from such an implementation.

Current tariff structures employed by ESKOM are Time-of-use (TOU) tariffs in the industrial sector. This includes the continuously varying Real-Time-Pricing (RTP) tariff, where 24 different hourly prices are supplied one day ahead of time. These tariff structures reflect typical peak demand periods experienced by the utility with higher pricing in these periods. In the commercial building sector, two tariffs are used extensively. The first tariff includes a 30-minute integrated peak demand cost which charges the owner for the maximum demand consumed in a month, together with a flat energy consumption rate. The second tariff is a two-part time-of-use tariff with different energy consumption rates for daytime and nighttime periods.

To obtain the DSM benefit for the utility is fairly uncomplicated in terms of what is required; namely a definite peak demand reduction in a specified period. To obtain a benefit for the client is however more complex. Simply shifting load out of the specified peak period is usually only partially beneficial, or sometimes of no benefit at all to the client.

- In the industrial sector, the client will obtain a benefit if the RTP or TOU tariff had a high price period overlapping with the utility's DSM period. This is usually the case, since the utility's peak load periods are reflected by high prices in these periods. There are however other periods when energy cost is high as well and where the industrial client can benefit from reducing load and shifting it to lower priced periods.
- In the commercial building sector, the client will obtain no direct benefit from the way utility funded DSM is currently applied in South Africa, since a maximum demand charge is included in the tariff. The client needs the electrical load to be as low as possible for typically more than 12 hours per day to avoid recording a maximum demand. Peak demand reduction for a specified period of one or two hours will therefore provide no benefit to the client based on this tariff structure. The client would even have to be careful for 'cold-load-pickup' effects directly after a DSM period, which can increase the facility's peak demand contribution and incur additional cost.

To obtain the maximum benefit for the client is of crucial importance to a DSM project, in order for the client to agree on making his facilities available for such a DSM project. The way of achieving this will be by exploiting the type of electrical tariff utilized by the client:

- Industrial RTP and TOU tariffs encourage clients to remove load out of high price periods, i.e. utility peak demand periods, into low price periods, i.e. utility off-peak periods. Energy cost is very low in these low- and medium priced periods, meaning that the emphasis lies more on load shifting than energy efficiency improvement. The focus will therefore be towards installing equipment that can achieve the required load shifting to increase cost effectiveness, without necessarily improving energy efficiency.

- Commercial tariffs encourage clients to both remove electrical load out of peak demand periods, and improve energy efficiency. This is due to energy consumption charges being generally much higher when compared to industrial tariffs. The focus will therefore be towards installing equipment that can achieve both peak demand reduction and energy efficiency improvements.

2 DSM programs for sanitary water heating systems

The heating of sanitary water via direct electrical resistance heaters remains one of the biggest contributors to the undesirable high morning and afternoon peaks imposed on the South African national electricity supply grid. These peaks are most prominent in the residential sector. The large sanitary water heating systems found in the commercial and industrial sectors are however also major load contributors during utility peak demand periods. Significant focus is therefore given by ESKOM in terms of financing DSM projects to exploit the current load situation. Previous theoretical and laboratory studies (Greyvenstein & Rousseau (1997), Rousseau *et al* (2000)) indicated that extensive application of the so-called in-line water heating methodology could result in significant peak demand reductions. This methodology makes use of either one hundred per cent electrical resistance heaters or a combination of heat pumps and electrical resistance heaters. It was also shown that commercial building owners who choose to implement the design methodology on existing or new systems could obtain impressive financial paybacks.

The need however exists to further optimize the methodology, to enable it to become an optimum Demand Side Management solution for both industrial and commercial applications. The different tariff structures utilized in the industrial and commercial sectors as well as differences in the consumption profiles and quantities will dictate different solutions. In the industrial sector where the focus is on pure load shifting, an in-line electrical resistance heater will be used, connected in the 'improved in-line water heating' configuration (Greyvenstein & Rousseau (1997), Rousseau *et al* (2000)). In the commercial sector where the focus is on both load shifting together with energy efficiency, a combination of heat pumps and in-line electrical resistance heaters will be used (Greyvenstein & Rousseau (1998), Rankin *et al* (2003)).

3 Scope of the study

The study is divided into eight chapters. Chapter 2 to Chapter 7 form the main body of the thesis, divided into two parts. Part one is made up of Chapters 2 to 4, and Part two of Chapters 5 to 7. Each of these chapters is written in the form of a journal article which includes its own abstract, introductory section with literature survey, main body, conclusion and references. The following sections provide a summary of the findings of the literature surveys of all the chapters and states the overall objectives and major contributions of the study as a whole.

3.1 Findings of the literature survey

An extensive literature survey has been done, which is provided in the introductory parts of Chapter 2 to Chapter 7. The most important findings are:

- Although several studies on sanitary hot water consumption patterns are reported, most of these studies only looked at hot water consumption in the residential sector. These consumption patterns have also been used up to now in the design of large sanitary hot water systems for buildings in the commercial sector. Consumption patterns will however be different in the commercial and industrial sectors due to differing usage patterns, when compared to the residential sector. This will have an effect on system design and should therefore be determined to enable the correct system design for a specific market sector.
- Several studies have been done on heat load forecasting models. Only one study (Rousseau (2000)) addressed sanitary hot water systems as a whole in a simulation routine, including storage capacity and water consumption profiles. This is also the only study incorporating the in-line water heating methodology as proposed by Greyvenstein and Rousseau (1997). A detailed monitoring investigation has recently been completed on large commercial sanitary hot water installations (Rankin *et al* (2003)). Comparison between results from this investigation and the above-mentioned model developed by Rousseau revealed a number of shortcomings. These shortcomings need to be addressed before accurate system operation predictions can be made.
- Previous optimisation studies were done for hot water system design in commercial buildings. These studies addressed only a limited range of system parameters. The need therefore exists to refine the design guidelines to include a broader range of design parameters. New optimisations are also required in the light of new data that became available, including hot water consumption profiles specific to commercial buildings.
- No previous work could be found that addresses the techno-economic optimisation of the in-line sanitary hot water heating system in the industrial sector. The Real-Time-Pricing (RTP) tariff employed in the industrial sector cannot be exploited optimally with only the standard analogue control systems currently employed. The need therefore exists for the development of a control system that can optimise the operation of sanitary water heating systems subject to RTP.

3.2 Objectives of the study

The main objectives of the study are:

- Part one of the study, which consists of Chapters 2 to 4, provides results of sanitary water heating projects completed at several commercial and industrial sites. All the systems referenced in Chapters 2, 3, and 4 were designed by the author. The author was also the responsible engineer during construction and commissioning activities at all the sites. The data obtained from these projects include new hot water consumption patterns for the commercial and industrial sectors that differ from residential sector profiles. The impact that these hot water consumption profiles will have on system design is analysed in Chapter 2. Comparisons of measurements and predictions as well as the successes achieved by implementation of DSM measures in these projects are also discussed and analysed in Chapter 3 for commercial buildings, and in Chapter 4 for industrial residences. Part one therefore provides the current status of the technology used in water heating system DSM projects. It also demonstrates that the technology developed in previous studies (Greyvenstein & Rousseau (1997), Rousseau *et al* (2000)) have been implemented successfully on a large scale on actual plants. The existing technology now provides a basis for further optimisations that will be addressed by Part two of this study.

- Part two, which consists of Chapters 5 to 7, provide results of optimisation studies for sanitary water heating system design in both commercial and industrial sectors. This is achieved by developing a water-heating system simulation program in Chapter 5 based on simplified first law analysis. Data obtained from the studies in Part one of the thesis is used to verify the accuracy of the simulation in predicting water heating system operation. Chapter 6 then evaluates several proposals for the optimisation of water heating systems in the commercial building sector. The in-line heat pump system as described in Chapter 3 is used as 'n basis for all optimisations. Finally Chapter 7 analyses the development of a control algorithm that optimises cost efficiency of hot water systems subject to the RTP tariff in the industrial sector. The optimised control algorithm is specifically developed for the in-line heater system as described in Chapter 4. Part two therefore provides guidelines to improve on the current water heating system designs in the commercial and industrial sectors respectively in order to increase the viability of DSM projects for both electrical utility and client.

4 Major contributions of the study

The major contributions of this study can be summarized as follows:

- New hot water consumption patterns are obtained for hotels, as well as for large residences in the mining industry. The impact that the new hot water consumption profiles have on water heating system design is evaluated through a simulation study, and significant differences are found when compared to current design practice. These differences are summarized by providing suitable design envelopes for conventional water heating systems in the residential, commercial and industrial sectors respectively. This may be used by practicing engineers in the design of new systems or the retrofit of existing plants.
- Although the in-line heating concept discussed in Chapter 3 and Chapter 4 was developed in previous studies, this study presents the first comprehensive proof of its effectiveness in actual water heating systems.

- A simulation model has been developed using a simplified first law analysis. The model addresses several shortcomings found in previous studies and simulation models. Verification of this model is made possible by the use of a lumped heat loss factor. This enables calibration of the model to obtain more realistic and practical results. The lumped heat loss factor calibration method enables the construction of an accurate baseline system complying with international measurement and verification protocols (IPMVP (2002)). This will enable direct comparison between different hot water system configurations at a specific hot water plant, or comparisons between similar systems at different plants.
- A generic design guideline for commercial building water heating systems is developed and evaluated. This guideline improves on previous design guidelines by providing optimal design capacities for different system parameters. The two electrical tariffs found in the commercial building sector have both been included in the optimisation phases. This improves on previous studies that only looked at 'maximum demand' type tariffs. The control algorithm for the in-line sanitary water heating system is improved by providing multiple stage control for the backup electrical resistance heater, which further improves demand reduction ability and economic viability of the system. Final control optimisation allows maximised runtime of the heat pump heater by allowing back-up heaters to operate only when really required, instead of being simply activated by a timer during off-peak periods each day. This further improves the energy- and cost efficiency of the system.
- An automatic control algorithm is developed which optimises cost efficiency of in-line sanitary water heating systems in the industrial sector subject to RTP. The algorithm includes a number of novel approaches to optimise the cost effectiveness whilst maintaining reliable hot water supply:

The above-mentioned aspects show that well-evaluated options for water heating DSM projects are provided, which can obtain benefits for both electrical utility and client. These options should therefore be able to boost the viability of water heating DSM projects in the Energy Services Industry.

5 Publications

A part of Chapter 3 of this thesis has been published in 2002 in the International Energy Efficiency in Commercial Building Conference proceedings, where the author presented the work. It was also published in 2004 as a full-length article in the international journal *Energy Conversion and Management (Elsevier)*. Chapter 2 of this thesis has been published in 2005 as a full-length journal article, also in *Energy Conversion and Management* journal.

PART ONE

APPLICATION OF THE IN-LINE WATER HEATING METHODOLOGY IN THE DSM INDUSTRY: CURRENT STATUS AND TRENDS

CHAPTER 2 - SANITARY HOT WATER CONSUMPTION PATTERNS IN THE COMMERCIAL AND INDUSTRIAL SECTORS IN SOUTH AFRICA: IMPACT ON HEATING SYSTEM DESIGN

Abstract

A large amount of individual sanitary hot water consumers are present in the South African residential sector. This lead to several studies focusing on hot water consumption patterns in this sector. Large amounts of sanitary hot water are also consumed in the commercial sector in buildings such as hotels, and in large industrial residences such as those found in the mining industry. No previous studies on hot water consumption patterns in the commercial and industrial sectors have been done. For this reason, residential hot water consumption patterns are currently used in water heating system design in the commercial and industrial sectors.

This chapter deals with actual hot water consumptions patterns measured in the commercial and industrial sectors. In the commercial sector results are provided for hotels, and in the industrial sector for large mining residences. Both of these types of facilities are served by centralised hot water systems. Measured results from the systems are compared to data obtained from previous publications.

Simulations are conducted for these systems using a simulation program developed in previous studies. The results clearly show significant differences in required heating and storage capacity when the different hot water consumption profiles are used in the simulation. A twin peak profile obtained from previous studies in the residential sector was used up to now in studies of heating demand and system design in commercial buildings. The results shown here illustrate the sanitary hot water consumption profile in hotels to differ significantly from the twin peaks profile, with a very high morning peak in hot water consumption. This leads to a requirement for bigger heating and storage capacities in commercial buildings like hotels. A summary of results is provided in the form of minimum design parameters for different hot water consumption profiles.

This study emphasises the importance of understanding the trends of hot water consumption in buildings, especially when Demand Side Management projects are done on these types of systems.

1 Introduction

The primary consideration in any DSM or energy efficiency project is to know and understand the way in which the energy produced by a process is consumed. This includes knowing whether the energy consumed is linked to a technical process that can be controlled, or whether energy is consumed in an uncontrollable manner. When energy is consumed by a process that cannot be controlled, the following important step would be to determine whether this energy consumption trend could be predicted to an acceptable degree of accuracy. The forecasting of electrical energy consumption would not be possible without being able to predict the consumption profile of the energy being produced.

Background to this problem is given by taking a look at ESKOM's direct customers. They include the mining, basic metals, chemicals, non-metallic minerals, municipal and transportation sectors. Most municipalities purchase their power from ESKOM, which makes up about 44% of the annual demand for electrical energy (NER (2003)). In the 1990s, ESKOM conducted a study on present and future national demand and gave estimated disaggregated weekly load profiles for various consumer categories (NER (2003)). The findings of the study indicated that the consumer groups that purchase power from municipal electricity undertakings, dominate the eventual level and shape of the national demand both in summer and winter. The primary municipal consumer groups are the residential and commercial sectors. The demand contribution of these consumer groups presents a challenge to the electrical utility not only because of the large number of individual consumers involved, but also because their load patterns are strongly linked to human behavior and not only the technology involved in the process. This is different to the industrial sector with a much smaller number of consumers and individual processes. These processes usually consume larges amounts of energy and are mostly not influenced by stochastic parameters such as human behavior.

One of the processes linked to human behaviour is the consumption of hot water for sanitary purposes. Previous studies (Greyvenstein & Rousseau (1999), Rousseau *et al* (2000)) have also shown that the heating of sanitary water in South African commercial and residential buildings is one of the biggest contributors to the undesirable high morning and afternoon peaks imposed on the national electricity supply grid. The heating of sanitary hot water is however not limited to the residential and commercial sectors. Centralised hot water systems also serve large residences for workers in industries like the mining sector. These sanitary hot water facilities at the mine residences consumes only a small fraction of the total energy consumption at a mine, but is still a significant amount and potential for load shifting should be present. Most of the heating done in these three sectors are by means of direct electrical resistance heaters.

The amount of hot water consumed as well as the daily and seasonal profile in which it is done remains the biggest stochastic parameter involved in sanitary hot water system design and simulation. Knowing and understanding hot water consumption patterns is very important when hot water systems are designed, and a lack of data can easily lead to incorrect design. For this reason several studies have been done regarding hot water consumption in the USA (Becker & Stogsdill (1990), Schipper (1982), Vine (1987), Barbour *et al* (1996), Batelle (1994), Abrams & Shedd (1996), ASHRAE (1987)) as well as in New Zealand (Carrington *et al (1985)*). Both Schipper and Vine have concluded however that hot water consumption is influenced by cultural and social norms. Schipper also found that American people generally use up to seven times more hot water than the citizens of certain developed European countries. This indicates that data from countries with certain cultural and social norms cannot be applied to countries differing in those aspects.

Five sources of reference can be found regarding hot water consumption in South Africa. Basson (1983) quotes a value of 50 liters of hot water consumed per person daily in the developed communities. In a study of the viability of heat pumps for water heating in the residential sector (Meyer & Greyvenstein (1992)), the value of Basson was adapted for the effect of seasonal changes on hot water use. This resulted in a value varying between 50 liters in summer and 75 liters in winter consumed per person daily. Beute (1993) used a value of 35 liters per person daily in his study of energy utilization in the residential sector. This is however an estimated figure and not based on any direct measurements. Meyer (2000) published several studies (Meyer & Tsimankinda (1997-1998)) based on a large-scale survey on hot water consumption in houses in both developing and developed sectors in South Africa. These studies indicated that hot water consumption varies between 75 and 120 liters per person per day in developed communities. These studies have been found to be the most comprehensive source of data currently available for hot water system design in the residential sector in South Africa. Greyvenstein & Rousseau (1999) and Rousseau *et al* (2000) refer to the database developed by Meyer in a study of the demand side management potential of sanitary water heating systems in commercial buildings. This implies that the database is also used for the design of large centralized hot water installations in commercial buildings.

The biggest consumers of sanitary hot water in the commercial sector are hotels, hospitals, and university residences. Strauss (1999) provides data on hot water consumption profiles for two university residences. No occupancy data is provided; therefore the amount of hot water consumed per person per day cannot be established from this data.

The survey shows that a number of references can be found on hot water consumption. None of the studies however addressed hot water consumption in commercial buildings like hotels, or mass residential areas like mining residences where large centralized hot water systems are found. A number of differences should exist in hot water consumption patterns between industrial, commercial and residential buildings; therefore a different hot water consumption pattern is expected. The aim of this paper is therefore to take a detailed look at hot water consumption patterns in hotels as well as industrial systems serving large residences. It also addresses the impact on system design of the different new profiles compared to those obtained previously for residential buildings.

2 Hot water consumption measurement in hotels

A demonstration project was launched in 2000 under the auspices of the Potchefstroom University for Christian Higher Education, to determine the viability of an "in-line heat pump water heating methodology" for DSM purposes in South African commercial buildings (Rankin *et al* (2003)). The aim of this project was to determine the current status of hot water system operation in hotels, and to demonstrate how this can be improved in terms of peak demand reduction and energy efficiency. Extensive measurements are taken at these installations to be able to compare different methodologies. Included in these measurements are complete thermal energy consumption measurements on each hot water system. This consists of water temperatures measured at the cold-water inlet of the facility and the outlet water temperature supplied to the building occupants, and water consumption measurement. Data from four hotels have been collected since February 2000, for a period of at least 12 months. Daily occupancy data for two of these hotels are also available for all measured periods. The comprehensiveness of the data available enables accurate determination of both daily and seasonal variations in hot water consumption patterns. The water consumption profiles can also be adjusted for a fixed outlet temperature, since inlet and outlet temperatures are also measured.

Results are shown in three different formats. Firstly the average monthly total consumption per person is calculated, showing seasonal trends in hot water consumption. Secondly the average daily total consumption per person is calculated and plotted against the daily occupancy. This shows the influence occupancy of a building will have on the total daily consumption of a centralized hot water system. Thirdly the normalized daily water consumption profile is determined based on 30-minute interval measurements.

All hot water consumption values have been adjusted for an outlet temperature of 60°C. This is required since the hot water outlet temperature can vary significantly within a specific hot water system. There is also a variation in set point values for different systems. This allows comparisons between different systems and for different periods on an equal available energy value per liter of hot water consumed. This adjustment is done by the following simple equation (Eq 1).

$$\dot{Q}_{corrected} = \dot{Q}_{measured} \cdot \frac{T_{outlet} - T_{inlet}}{60 - T_{inlet}} \qquad \textbf{Eq 1}$$

2.1 Seasonal hot water consumption patterns

Data was obtained from two hotels. These were specifically chosen due to the fact that complete occupancy data was available for each hotel and both installations have been continuously monitored for more than a year. The two hotels belong to the same franchised group of hotels, but are situated in different climatic regions. The one installation is situated in Johannesburg with a moderate climate and mostly summer rainfall. The other installation is in Cape Town with a coastal climate and predominantly winter rainfall. Both hotels have the same number of rooms and both have exactly the same sanitary facilities per room, e.g. bath, shower and basin. There is a central kitchen preparing breakfast according to the previous night's occupancy, as well as a central laundry facility. Figure 1 shows the measured monthly average water usage per occupant.

The standard deviation from the average values varied between 14% during summer and 30% during winter for both hotels. It can be seen from Figure 1 that an average of 93.5 liter of hot water per person is consumed in the Johannesburg hotel, and 72.5 liter in the Cape Town hotel. Hot water consumption in the Johannesburg hotel varied from a minimum of 78.5 liter in summer (January) to a maximum of 109.6 liter in winter (July). Hot water consumption in the Cape Town hotel varied from a minimum of 64.4 liter in

January to a maximum of 84.4 liter in July. This implies that hot water consumption typically increases with 40% from summer to winter in the Johannesburg hotel and with 30% in the Cape Town hotel. The difference between summer and winter consumption can probably be attributed directly to ambient conditions. The cold water temperature supplied to the showers or baths is higher during summer. The typically required mixing temperature between hot and cold water is also lower for a shower or a bath during summer. This means that the hot water fraction becomes smaller relative to the cold-water fraction used in summer.

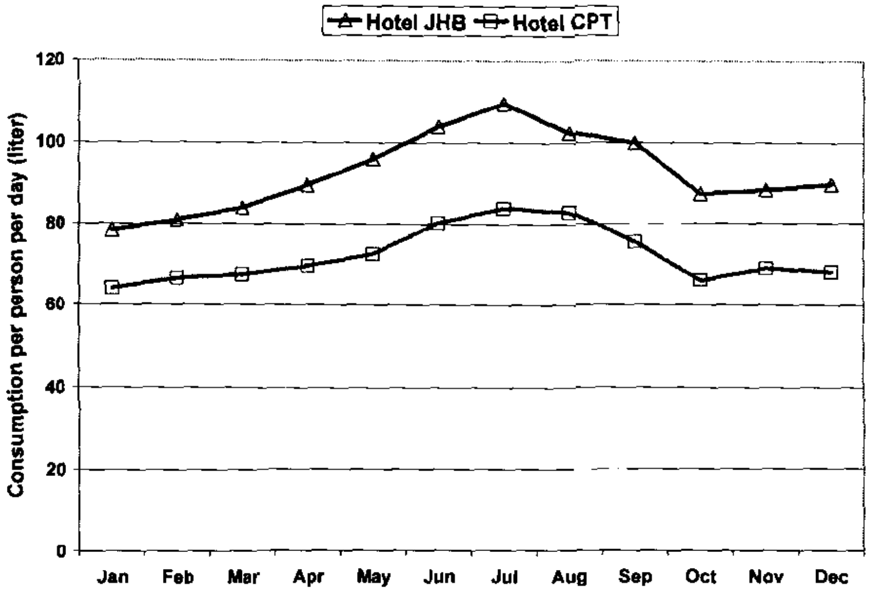


Figure 1: Hot water consumption per person per day, corrected at 60°C for a 12-month period

From the 12 months data it can be seen that there is an average difference of 23% in hot water consumption between the Johannesburg hotel and the Cape Town hotel. The difference in water consumption can be attributed to a number of factors, of which the most important are mentioned below:

- The operational status of the hot water circulation ringmain system is different for the two hotels. In the Cape Town hotel the flow rate through the ringmain return system is quite high, meaning that hot water is almost always readily available at the taps in each room. The drawback of this approach is however that significant heat loss occurs in the ringmain system, which lowers the overall efficiency of the hot water system. The flow rate through the ringmain system in the Johannesburg hotel is set much lower for the purpose of conserving energy. Therefore the rooms furthest from the hot water system generally need to draw a significant amount of water from the storage tanks before water at an acceptable temperature is available.
- The climate in Cape Town is in general significantly warmer than the climate in Johannesburg. This means that people will typically use less hot water in Cape Town because of the warmer climate there.

2.2 Daily hot water consumption versus occupancy

This section describes the influence of the total occupancy in a hotel on the amount of hot water consumed per person per day. For this purpose the day-to-day change in occupancy of a hotel needs to be taken into account, including the exact period of hot water consumption associated with a certain occupancy figure. It is important not to simply use the daily water consumption total from 0:00-24:00, since the occupancy can vary between two days from as few as 30 guests one night to 200 guests the following night. All of the hotels allow room occupation from 14:00, and booking out of the hotel needs to be done before 11:00. The previous night's occupancy will however still influence hot water consumption between 11:00 and 14:00, since the laundry operates during this time, washing linen from the previous night. The occupancy for a specific night therefore influences the hot water consumption from that afternoon at 14:00 to the following afternoon at 14:00.

Figure 2 shows a multiplication factor related to the normalized hot water consumption per person, versus the occupancy, which is expressed as a fraction of the maximum occupancy for the Johannesburg hotel.

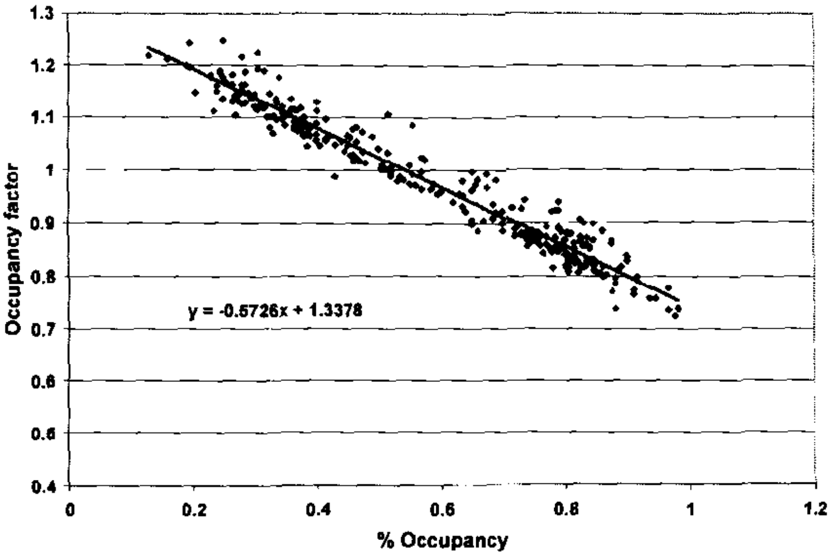


Figure 2: Influence of total occupancy per day on hot water consumption per person

The normalized hot water consumption has been corrected with seasonal factors to remove the seasonal variations as obtained in the previous paragraph from the data. It can clearly be seen that the normalized hot water consumption per person increases with decreased occupancy. For instance, when occupancy is only 30% of the maximum, the hot water consumption per person will be 16.6% higher than the average as obtained in the previous section. For high occupancy levels (90%), the hot water consumption per person will be 17.8% lower than the average. The following reasons are provided.

- When a person occupying a room near the end of the ringmain supply piping of the building draws hot water, a large amount of water needs to be drawn before hot water becomes available at the tap. A significant amount of water is therefore simply wasted. If the occupancy of the building is high, the associated higher consumption of hot water will ensure that the ringmain remains relatively hot, and less hot water will be wasted in this manner.

- The laundry facility and kitchen of the hotel requires a certain minimum amount of water to operate, regardless of the amount of linen to be cleaned, or the number of meals to be served. A base hot water load therefore exists which is not dependant on occupancy. When the occupancy is low, this base load will represent a significant fraction of the total hot water consumption, and this will increase the normalized hot water consumption per person per day.

From the trend line in Figure 2 the following equation is obtained:

$$y = -0.5726 \cdot x + 1.3378 \qquad \textbf{Eq 2}$$

with y representing the normalized hot water consumption adjustment factor, and x the occupancy, expressed as a fraction of the maximum occupancy of the building.

This equation can be used in system design and simulations together with seasonal correction factors to determine the typical water consumption for certain occupancy. This will enable a more accurate determination of the system operation as opposed to using only average water consumption per person. If only the average water consumption per person is used together with the maximum occupancy to determine the maximum amount of water consumed, the system might be over designed in terms of heating or storage capacity. The potential for heating load shifting might not be shown in simulation results if the water consumption at maximum occupancy is over-estimated.

It is however important to note that this equation should only be used in designing systems that are similar in layout and operation. The similarities required are the utilization of a long ringmain system typical to hotels, and the presence of a central kitchen and laundry facility. Should these aspects differ significantly from the case study system, a different relation between occupancy fractions and total hot water consumption might exist. This means that the equation cannot always be applied to any hot water design. It does however illustrate that occupancy fractions can have a significant influence on the amount of hot water consumed per person.

2.3 Resultant 24-hour profiles obtained from 30 minute measurements

This section provides the daily profile of hot water usage for two of the hotels mentioned. The profile shown is normalized, meaning that hourly hot water consumption values are expressed as a fraction of the daily total hot water consumption, It also represents the weighed average obtained from at least 12 months water consumption and occupancy data. Data points represent the accumulated water consumption value for the following time period, i.e. the 9:00 data point shows the total water consumption for 9:00-10:00. From Figure 3 a striking similarity can be observed for the water consumption profiles of the two hotels. Both hotels show a very high peak hot water demand early in the morning, with the Johannesburg hotel hot water demand peaking at 7:00, and the Cape Town hotel peaking at 8:00. This difference can be attributed to sunrise, which is typically one hour later in Cape Town compared to Johannesburg, and this leads to a difference in the office hours in these cities of typically one hour. Both hotels show a smaller but still significant peak at noon, which can be attributed directly to operation of the laundry facility at both hotels as well as room cleaning. An evening peak also occurs between 19:00 and 22:00, although this peak is only about 35% of the morning hot water demand peak. The maximum standard deviation from the average values shown in Figure 3 was 17% for both summer and winter measurements.

These profiles show that typically 60% of the daily hot water consumption occurs between 6:00 and 13:00 for both hotels. This very high demand in a relatively short period will significantly influence the design of a hot water system, with either a large storage capacity or large heating capacity required. If the heating capacity of the system is sized to spread the heating load evenly over a 24-hour period for DSM purposes, the storage capacity needs to be sufficient to provide hot water for the large morning peak without hot water run-out. This issue will be discussed in more detail in following sections.

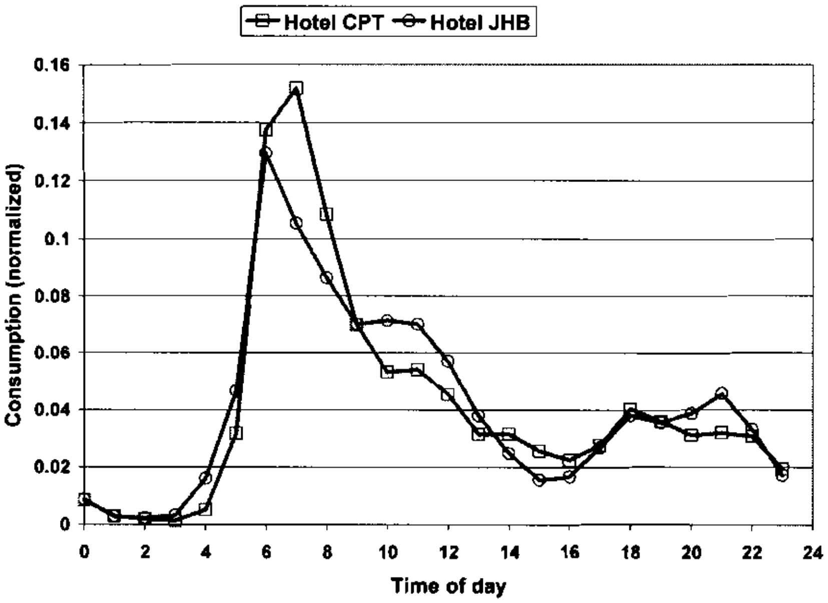


Figure 3: Hourly normalized hot water consumption per person per day

3 Hot water consumption patterns in large residences in the mining sector

A sector where large amounts of hot water are consumed is in large residences in the industrial sector. Mass labor is required in industries like mining, and since most of these workers are coming from rural areas, accommodation is provided for them in the form of large residences, with occupancy ranging from 1500 to 5000 occupants per residence. Large centralized hot water systems provide sanitary hot water for showering and washing purposes. These systems are utilized heavily by residents, due to the nature of work in the mining sector underground in extreme ambient and dusty conditions.

Projects are currently implemented, funded by ESKOM's Demand Side Management initiative (ESKOM DSM), to reduce the electrical demand of these centralized hot water systems during certain peak periods. Part of the initial investigation was to determine the hot water demand, as well as the 24-hour consumption profile. This data is presented in this section.

3.1 Seasonal hot water consumption patterns

Data was obtained from six mining residences over a period of 11 months. A difference between these mining residences and hotels is that the occupancy does not vary on a day-to-day basis. The reason for this is that leave is granted to workers on a yearly rotational basis, in order to have a constant working force available throughout the year. Showering facilities are also situated adjacent to the hot water system, and therefore no ringmain circulation system is used. Hot water consumption for a specific mine residence is therefore not influenced by effects caused by varying occupancy, but only by seasonal variations in ambient and water temperatures.

Figure 4 shows the average hot water consumed at 60°C per person per day, for a 12-month period. The patterns compare well to the seasonal variation seen in the previous section for hotels, as well as published data for the residential sector (Meyer 2000). Maximum standard deviations varied from 17% during summer to 24% in winter.

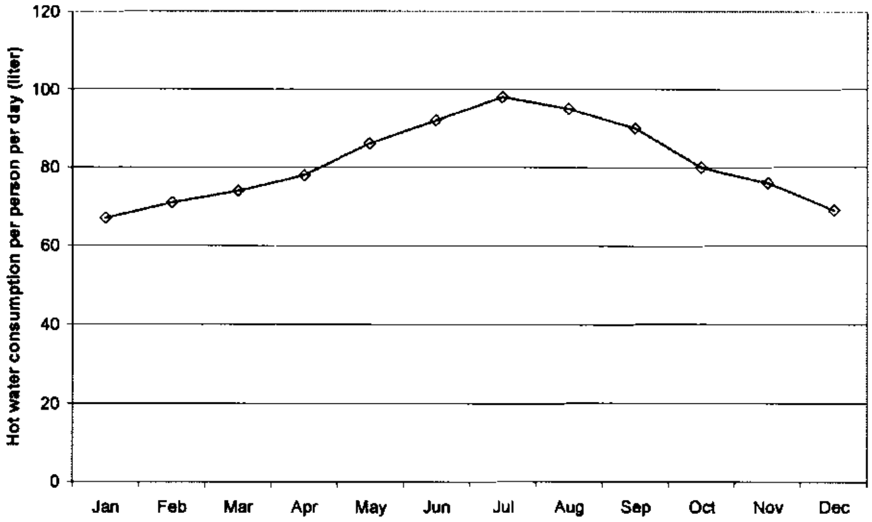


Figure 4: Hot water at 60°C consumed per person per day, for a 12-month period

An average of 81 liters per person per day was consumed during the 12-month period, ranging from a minimum of 68 liters in summer (January), to a maximum of 96.5 liters in winter (July). A maximum difference of 41% exists between summer and winter consumption, which compares well to the 40% summer to winter difference obtained for the Johannesburg hotel in section 2.1. The mine residences are situated in the same climatic region as the Johannesburg hotel. It can therefore again be concluded that seasonal variations in ambient conditions are the main reason for the variation in hot water consumption throughout the year.

3.2 Resultant 24-hour profiles obtained from 30 minute measurements

This section provides the daily hot water consumption profile for the six mine residences. The profile shown in Figure 5 is normalized and represents the average obtained from all the data.

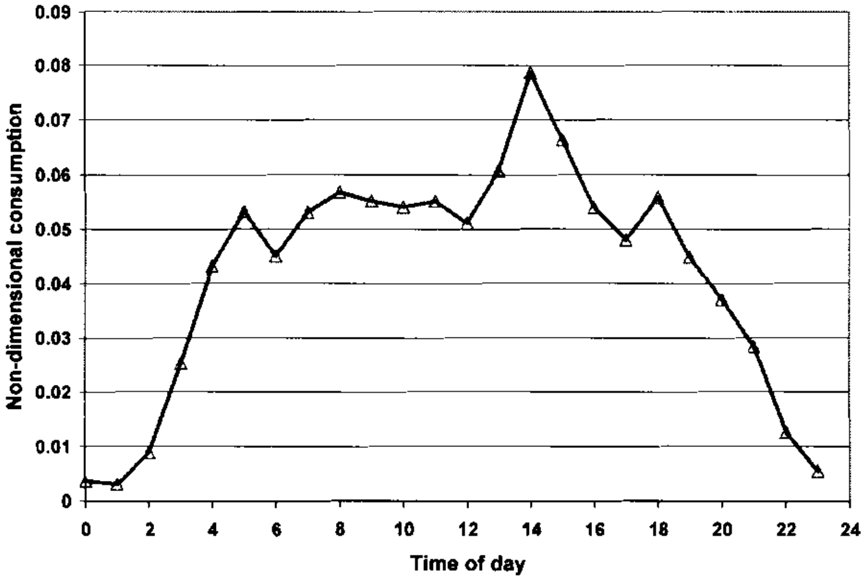


Figure 5: Normalized 24-hour consumption profile for mining residences

From Figure 5 a different profile is seen when compared to the profile obtained for the hotels in the previous section or the profiles from previous publications (Meyer 2000). Peak hot water consumption, totaling 21% of the daily hot water consumption occurs between 14:00 and 16:00, which represents the time when the main working shift is completed. The rest of the demand for hot water is spread almost evenly between 5:00-20:00, with no significant peaks or troughs. Only after 20:00 until 5:00 in the morning the hot water consumption declines below the average figure for a 24-hour period.

4 Influence of hourly hot water demand profiles on water heating system design

The new hot water consumption profiles shown in the previous sections differ significantly from profiles obtained in the literature. Meyer & Tsimankinda (1997-1998), Becker & Stogsdill (1990) and Carrington (1985) all provide hot water consumption profiles for the residential sector, and all three studies showed profiles with distinctive morning and evening peaks of basically the same size, called the twin peaks profile. This differs from the profile obtained in Figure 3 for hotels, with 60% of the total hot water consumed during the morning peak, compared to only 35% of the total hot water consumed per peak period in the twin peaks profile obtained by Meyer and Tsimankinda (1998). The profiles also differ significantly from the mine residence profile, where hot water consumption occurs almost constantly between 5:00-20:00 each day, with a peak period occurring between 14:00-16:00. This section attempts to address the influence these different profiles will have on hot water system design.

4.1 Required heating and storage capacity for different hot water consumption profiles

Rousseau *et al* (2000) developed a deterministic simulation model for water heating. This model simulates the heating load taking into account water consumption profiles and outdoor air temperature changes, including seasonal variations. The model has been verified using a laboratory test rig, and found to provide an acceptable degree of accuracy in simulating systems based on both in-line and in-reservoir heating configurations. It makes use of a multi-node temperature distribution model, whereby the storage reservoir is divided into several control volumes for which mass and energy conservation is solved at each time-step. The deterministic model was embedded within a stochastic approach that allows long-term predictions based on a Monte-Carlo analysis. The study utilizes the database developed by Meyer in a study of the demand side management potential of sanitary water heating systems in commercial buildings. This simulation model will be used to demonstrate the impact of different hot water consumption profiles on the system design. In order to make the comparisons as generic as possible, all variables will be expressed as non-dimensional variables.

Non-dimensional temperature is defined as follows:

$$T^* = \frac{T_{actual} - T_{inlet}}{T_{set} - T_{inlet}} \qquad \text{Eq 3}$$

with T_{actual} the actual measured outlet temperature, and T_{set} the set-point temperature of the system.

Non-dimensional heating capacity is defined as follows:

$$Q^* = \frac{Q}{\rho \cdot V_{day} \cdot c_P \cdot \Delta T / (24 \cdot 3600)} \qquad \text{Eq 4}$$

with Q the installed heating capacity, ΔT the maximum temperature difference between the hot water system inlet and supply, and V_{day} the maximum amount of hot water consumed daily.

Non-dimensional storage capacity is defined as follows.

$$V^* = \frac{V}{V_{day}} \qquad \text{Eq 5}$$

with V the installed storage capacity of the system.

Figure 6 provides a comparison between the different water consumption profiles as obtained in this study and in previous studies. The hotel profile boasts the most significant peak period. The consumption peaks of the residential profile (twin peaks profile provided by Meyer (2000)) and the mine residence profile are very similar, although two peaks occur in the twin peaks profile and only one peak in the mine residence profile.

These profiles are now provided as input to the simulation program, and a minimum value of T^* =0.8 is prescribed throughout the simulation day as a design constraint. Any combination of heating and storage capacity resulting in $T^*<0.8$ will not be considered a viable design, since the quality of hot water supply to the users of the system is then compromised.

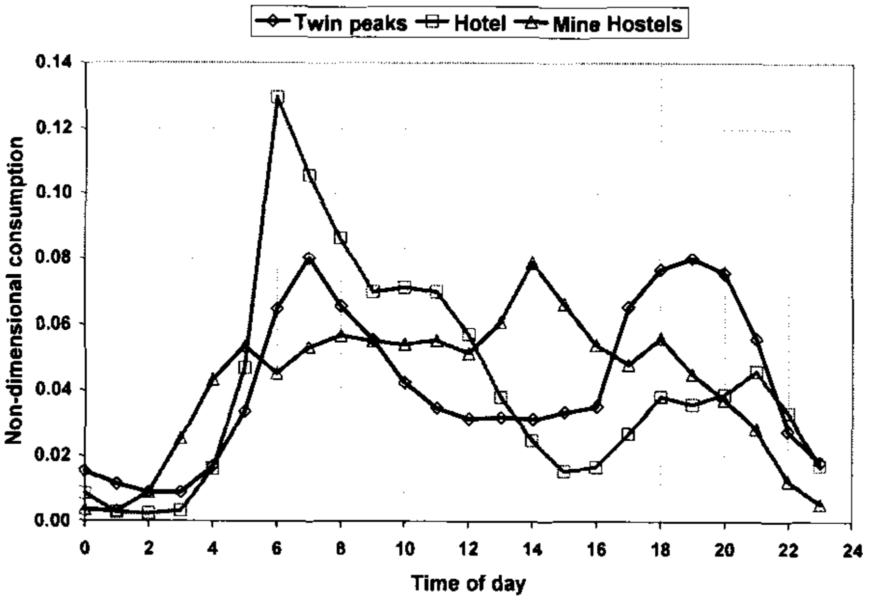


Figure 6: Comparison between different water consumption profiles

Figure 7 to Figure 9 show the results of the simulations of a conventional in-tank heating system, for each water consumption profile. When hot water is consumed according to the twin peaks profile, the hot water installation can be designed with a non-dimensional heating capacity of $Q^*=1.75$, combined with a non-dimensional storage capacity of $V^*=0.4$. This is a similar result as obtained in a previous study by Greyvenstein & Rousseau (1999), where the twin peaks profile was used to determine system design variables for commercial building heating systems. A non-dimensional heating capacity of $Q^*=1.5$ will be sufficient if the non-dimensional storage capacity is $V^*=0.6$.

If this is compared to the simulation results for the hotel profile, very significant differences are observed. For a non-dimensional storage capacity of $V^*=0.4$, a minimum non-dimensional heating capacity of $Q^*=2.50$ is now required, which is 43% higher than that of the twin peaks profile. For $V^*=0.6$, a minimum non-dimensional heating capacity of $Q^*=2.00$ is required, which is 33% higher than that of the twin peaks profile.

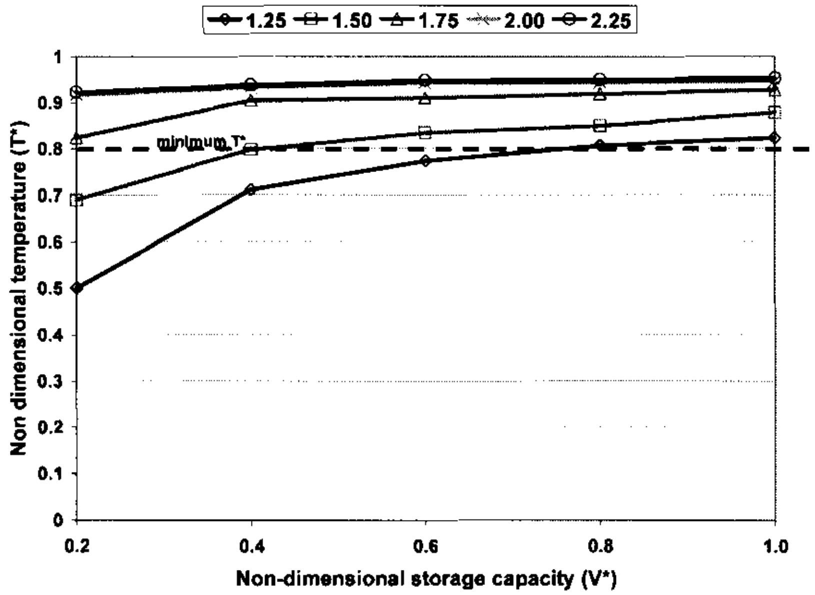


Figure 7: T as a function of V* and Q* for the twin peaks profile*

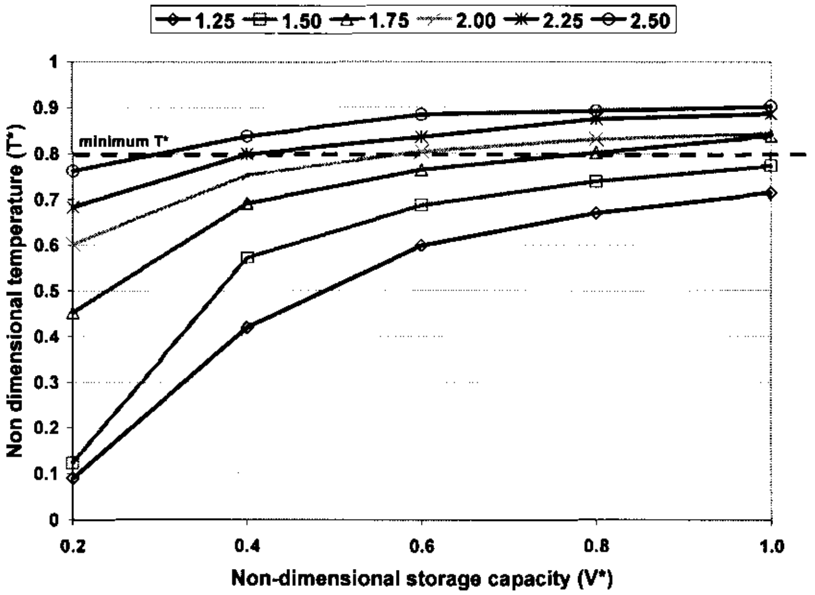


Figure 8: T as a function of V* and Q* for the Hotel profile*

These results clearly show that the hot water consumption profiles have a significant influence on hot water system design. Previous studies (Greyvenstein & Rousseau (1999), Rousseau *et al* (2000)) on heating demand and hot water system design in commercial buildings were conducted using the twin peaks profile, which was actually obtained from measurements on high and medium income houses in the residential sector. Results from this study indicate that the required heating and storage capacities are higher when water is consumed according to the hotel profile obtained from this study.

Results for the mine residence profile show some similarity to the results of the twin peaks profile, although the requirements on storage capacity are lower for $Q^*<1.75$. For a non-dimensional storage capacity of $V^*=0.4$ and higher, a minimum heating capacity of only $Q^*=1.50$ is required, and for a non-dimensional heating capacity of $Q^*=1.75$ or higher, a non-dimensional storage capacity of only $V^*=0.2$ is required. This result correlates well with the systems typically found in this sector.

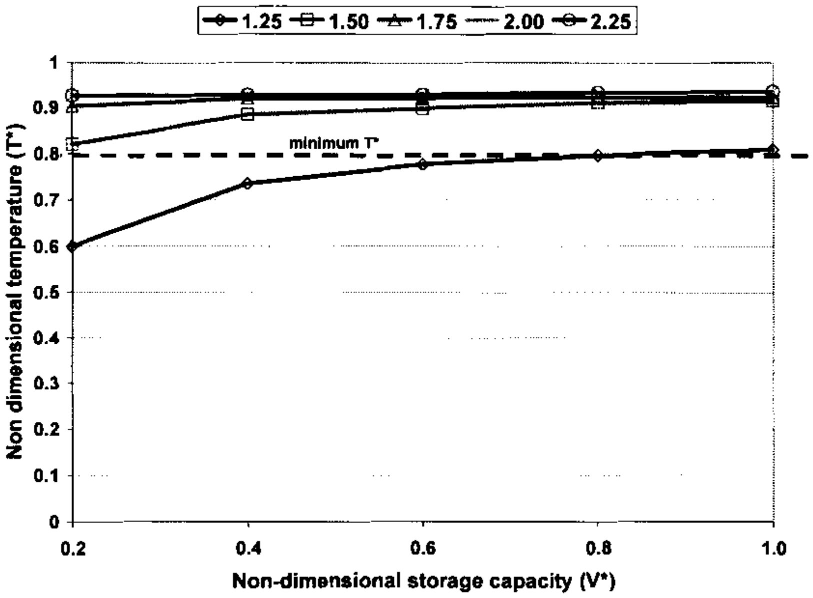


Figure 9: T as a function of V* and Q* for the Mine residence profile*

These differences can be explained by looking at the peak hot water consumption periods for the three different profiles, as shown in Figure 6. The hot water consumption peak for hotels is 65% higher than the hot water consumption peaks in the twin peaks profile. This leads to a 33% bigger heating capacity required for the hotel profile when compared to the requirement for the twin peaks profile, at a typical non dimensional storage capacity of $V^*=0.6$.

Even more significant a difference would be seen when the heating capacity of a sanitary hot water system is minimized for Demand Side Management purposes. If a non-dimensional heating capacity of $Q^*=1.75$ is proposed for a system, the minimum storage capacity for the twin peaks profile is only $V^*=0.4$, compared to a minimum storage capacity required of $V^*=0.8$ for the hotel profile.

Results for the mine residence profile shows the sizing of the storage capacity in this sector to be far less critical compared to the hotel systems. A very low non-dimensional storage capacity coupled to an appropriate heating capacity should be able to supply hot water throughout the day, due to the almost constant hot water demand profile obtained from the industrial sector residences.

5 Minimum design parameters

From the simulation results obtained in the previous section, certain minimum requirements for system heating and storage capacity are observed. Figure 10 provides a summary of the allowable design envelope for conventional hot water systems based on the different profiles. This also illustrates the difference between hotel and residential twin peaks profiles, and the similarity between the mine residence and residential twin peaks profiles.

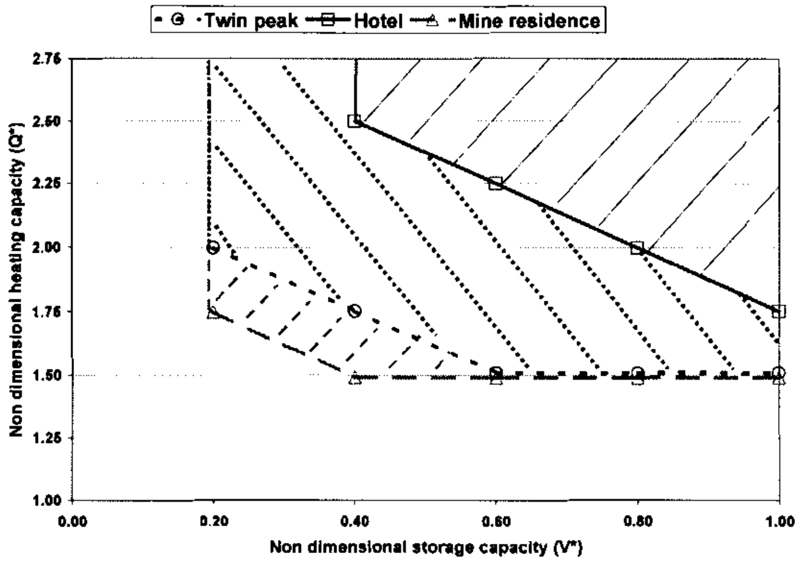


Figure 10: 'Minimum required' design parameters for different hot water consumption profiles

6 Conclusion

This chapter provides information regarding hot water consumption in South African hotels, as well as in large mine residences. Measurements of hot water consumption in hotels and mine residences correspond well with data from previous studies (Meyer 2000) in terms of the total amount of hot water consumed per person. Data from their study for low-density (high-income) type housing is very similar to the total consumption per person in hotels. Significant differences are however seen between the residential and commercial hot water consumption profiles. These profiles impact significantly on system design as shown in the previous paragraph, meaning that system design capacities might be determined incorrectly if the data from previous studies were used.

Another important parameter that is quantified in this paper is the influence of occupancy levels in hotels on the nominal hot water consumption per occupant. Measured results showed that the hot water consumed per person increases for decreasing occupancy. This is attributed to certain base loads that are present, which are independent of occupancy, as well as variations in the utilization of the ringmain system circulating hot water through the building. The resulting equation for normalized consumption as a function of occupancy can be used in system design to correctly determine hot water consumption for any given occupancy level in similar water heating systems in hotels.

Knowing and understanding the trends of hot water system usage generally improves the Demand Side Management potential of any project concerned with hot water installations. Not only will the storage- and heating capacity be sized correctly, but also the control algorithms and set points of the system can be adjusted accordingly, to obtain maximum Demand Side Management potential without a loss in hot water availability. Previously, systems were either over-designed to avoid hot water deficiencies, with obvious peak electrical demand penalties involved, or systems were designed for minimum electrical demand contribution, disregarding the issue of hot water availability. This study was done specifically on hotels where insufficient hot water supply is not an option, meaning that these systems are typically over designed. This in turn means that a definite peak demand reduction potential exists in most hotels. This will however only be realized if the hot water consumption behavior is understood and incorporated into design and optimization tools for sanitary water heating systems.

CHAPTER 3 - DEMAND SIDE MANAGEMENT FOR COMMERCIAL BUILDINGS USING AN IN-LINE HEAT PUMP WATER HEATING METHODOLOGY

Abstract

The previous chapter analyzed hot water consumption profiles obtained during a demonstration project for in-line heat pump systems in commercial buildings. This chapter takes a look at the implementation of the in-line heat pump system at the case study hotels. Data is presented from these installations, where the issues of Demand Side Management and energy cost reduction are addressed.

Results based on actual data from the monitored installations show a significant peak demand reduction for each installation. In one installation, a hotel with occupancy of 220 people, the peak demand contribution of the hot water installation was reduced by 86%. This resulted in a 36% reduction in peak demand for the whole building. The savings incurred by the building owner also included significant energy consumption savings due to the improved energy efficiency of the heat pump water heater. The combined savings resulted in a conservatively calculated straight payback period of 12.5 months, with an internal rate of return of 97%.

Based on these preliminary results, it is estimated that a total peak demand reduction of 108 MW can be achieved if this methodology can be implemented throughout the South African commercial building sector. This represents 18% of the peak load reduction target set by ESKOM until the year 2015, with an associated avoided cost of approximately MR 324 (ZAR).

1 Introduction

The previous chapter focused on the consumption of sanitary hot water in commercial and industrial facilities. From the results obtained, it is clear that large amounts of sanitary hot water are consumed in commercial buildings such as hotels. In this chapter the focus is shifted towards the water heating facility in these buildings. Unlike in the United States of America and most European countries, South Africa has very few accessible commercial supply networks of natural gas. Therefore, most of the sanitary hot water used in South African buildings is heated by means of direct electrical resistance heaters. Previous studies (Greyvenstein & Rousseau (1997, 1999)) showed that this is a major electrical load contributor. For this reason there is a definite peak demand reduction as well as energy efficiency improvement potential at these installations.

Previous studies (Rousseau *et al* (2000)) conducted by the Potchefstroom University for Christian Higher Education in South Africa indicated that extensive application of the so-called in-line heat pump water heating methodology in commercial buildings could result in significant Demand Side Management savings to ESKOM. Furthermore, building owners who choose to implement the design methodology on existing or new systems can achieve significant cost reductions with good payback periods. These savings are obtained by a significant decrease in the building's peak electrical demand, as well as a decrease in the building's energy consumption with the improved energy efficiency of a heat pump water heater.

These preliminary results prompted the need for a demonstration project to determine the potential of the methodology. It also needs to be established as a proven concept in practice, supported by references to various successfully implemented systems. The impact of variations in building type, hot water storage capacity, consumption profiles, as well as geographical location and climate needs to be investigated. This was done through the retrofit installation of various sanitary water heating facilities in commercial buildings such as hotels, with varying occupancy and storage capacity, in different climatic regions. Results from these installations are used to determine the impact of all the variables involved, as well as the continuous upgrading of the control algorithms of the system, to be able to realize the full demand side management and energy saving potential. This chapter will focus on the results obtained during the demonstration phase of the project, for three different installations.

2 Methodology

2.1 Conventional design philosophy

At present most of the water heating plants in South African commercial buildings are based on the conventional in-tank configuration shown in Figure 1. Surveys showed that most of these installations are designed according to guidelines set by EPRI (Abrams (1992)) and ASHRAE (2003). This configuration has electrical heating elements and a control thermostat installed inside the reservoir, usually near the bottom.

In the in-tank configuration the water is heated gradually at the bottom of the reservoir and the supply water is drawn from the top. This means that whenever hot water is drawn from the top, cold water entering at the bottom of the reservoir will lower the temperature at the thermostat. The thermostat will then normally call for the full heating capacity to be activated. This configuration therefore causes the system to activate the full heating capacity whenever the building occupants consume hot water. The effect of this is therefore that the electrical demand profile for the installation shows distinctive peaks. These peaks coincide with the hot water consumption peak periods in commercial buildings that were demonstrated in Chapter 2.

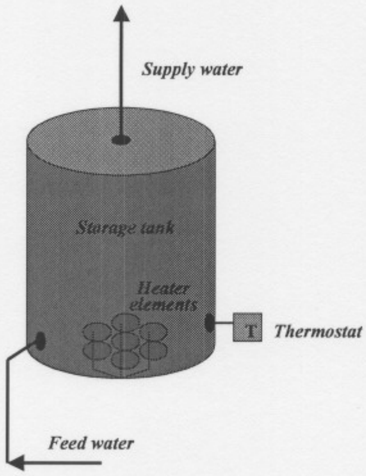


Figure 1 – Conventional in-tank heating configuration

The fact that the heating is done at the bottom implies that the water in the reservoir is usually well mixed (Pate (1977), Hendricks (1993)). This leads to the average water temperature being lower than the desired set point value. This is not an ideal situation to have during a peak hot water demand period. Furthermore, if the reservoir is filled with cold water after a prolonged period of hot water usage, practically all of the water in the reservoir needs to be reheated to the desired temperature before any of the hot water is available at that temperature. This design philosophy therefore requires that the heater must be able to reheat the total content of the reservoir within a short period of typically three to four hours. This implies that a large heating capacity is needed to obtain this requirement. Through an extensive survey done as part of this project, it was found that the installed heating capacity in commercial buildings in South Africa is typically 0.7 kW/person.

2.2 Improved in-line heating configuration

An improved in-line heating configuration combined with a heat pump water heater, proposed by Greyvenstein and Rousseau (1997,1999), is shown in Figure 2. In the in-line heating configuration the hot water produced by both the heat pump and electrical resistance in-line heater is returned to the top of the storage tank instead of to the bottom. The circulation system includes a control valve that regulates the flow rate through the heater in such a way that the water leaving the heater is maintained at the desired set point temperature. This means that for a fixed heating capacity and outlet temperature, the flow rate is varied through the valve for varying inlet temperatures. If the reservoir is filled with cold water, the hot water supplied by the heater back to the top of the storage tank is always at the regulated temperature. Since the water is added at the top, a well-defined temperature gradient will be maintained. This ensures that even though the average water temperature in the storage tank may be much lower than the set point value of the thermostat, a certain volume of water at the top will always be ready for use at the desired temperature, even if most of the storage tank is filled with cold water after a peak water demand period. This design philosophy therefore does not require the water to be heated in a short period, due to better utilization of the available storage capacity. The total amount of water required by the building per day can be heated gradually over a 20 to 24 hour period, thereby realizing a significant reduction in the required installed heating capacity. It is therefore clear that this system lends itself much better towards commercial DSM.

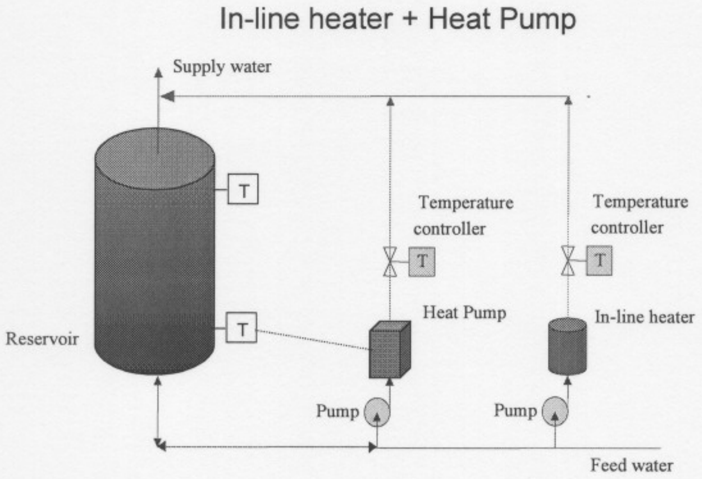


Figure 2 – Improved in-line heating configuration combined with a heat pump

Previous studies (Rousseau *et al* (2000)) have shown that the application of the in-line heating methodology could reduce the heating capacity required by an average of 58%. If this heating methodology is however combined with a heat pump heater, the peak demand could be reduced theoretically by a further 60%, meaning a combined peak demand reduction of 83%. The heat pump furthermore has the ability to reduce the electrical energy consumption of the hot water installation by typically 66 %. This realizes a combined benefit for the building owner of a significant peak demand reduction, as well as significant savings in the cost of electricity consumption.

3 Measurements taken at each installation

Each of the installations in the project is installed with a monitoring system. This system consists of a data logger installed on site that communicates via radio networking with a Central Processing Facility (CPF), where the data is stored and displayed. These measurements include a number of temperatures, flow rates and electrical power measurements. A typical example of the type of measurements taken is shown in Figure 3. The standard uncertainties associated with the direct measurements are shown in Appendix C of the thesis.

These measurements are used to obtain all the important parameters to be able to verify the peak demand reduction and energy saving potential of the installation. The uncertainties of all the parameters calculated using the direct measurements is also calculated in Appendix C. Uncertainty calculations are based on the guide to the expression of uncertainty in measurement as provided by the International Standards Organization (1993).

The following parameters are needed for validation purposes:

- kVA measurements for the building, heat pump heater and back-up electrical heater.
- Thermal energy output of the heat pump and electrical back-up heater, and thermal energy consumed by the building. The thermal energy is calculated as a function of measured inlet and outlet temperatures, and flow rates for each heater and that of the building supply.
- Dry bulb temperature and relative humidity measurements.

All of the measurements are available on a 30-minute basis, and kVA demand measurements are integrated over this 30-minute period, complying with the electrical utility's kVA demand measurement standard.

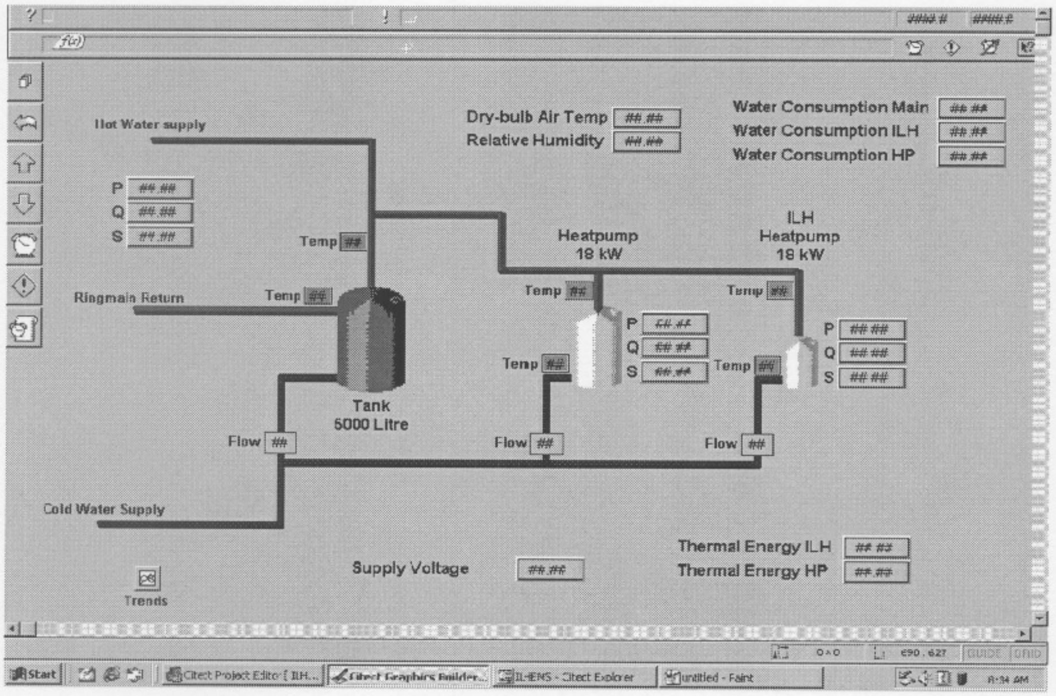


Figure 3 – Lay out of measurements taken at an installation

4 Results

Three installations have been completed and monitored in the project. These installations vary in terms of occupancy, storage capacity and climatic region, and therefore results vary slightly. All three installations have however proven to be very successful, with good cost savings and payback periods for the building owners. A significant peak demand reduction is also obtained to the benefit of ESKOM. Table 1 shows basic specifications for the three installations. Resultant demand profiles for all three installations, before and after the retrofit, will be displayed and discussed. The energy efficiency improvements obtained by the heat pump will be analyzed in detail for the first case study. A summary of the results of all three installations is given in each section.

Table 1: Specifications of three installation case studies

	Maximum occupancy	Storage capacity	Installed heating capacity before retrofit	Installed heating capacity after the retrofit	Typical ambient conditions
Case study 1	220	8000 liters	192 kW	40 kW (Heat pump) 54 kW (Electrical heater)	-4 to 32 °C
Case study 2	84	5000 liters	54 kW	16 kW (Heat pump) 27 kW (Electrical heater)	-4 to 32 °C
Case study 3	242	16000 liters	168 kW	40 kW (Heat pump) 60 kW (Electrical heater)	-1 to 29 °C

4.1 Measured Demand Side Management impact

Case study 1

Figure 4 shows the measured typical daily peak demand profile of the water heating installation as well as the total hotel complex before the retrofit, for case study 1. Data points represent the integrated load value for the following 30-minute period, i.e. the 9:00 data point shows the integrated electrical load for 9:00-9:30. It clearly shows that the peak demand of the water heating installation coincides with that of the building complex and therefore directly contributes to the total peak demand costs. At 21:00 when the maximum demand is registered, the water heating installation contributes 130 kVA and the rest of the hotel complex 149 kVA.

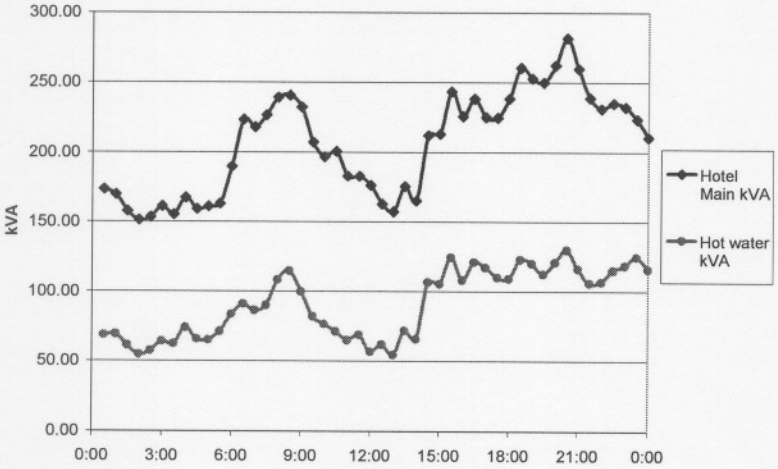


Figure 4 – Typical diurnal kVA demand before retrofit installation in case study 1

The retrofit installation included the replacement of the heaters with a 40 kW heat pump that was specifically designed for the in-line heating concept. An in-line electrical resistance heater with a heating capacity of 54 kW was installed as a back-up heater. The installation of the heat pump unit on the roof of the hotel complex is shown in Figure 5.

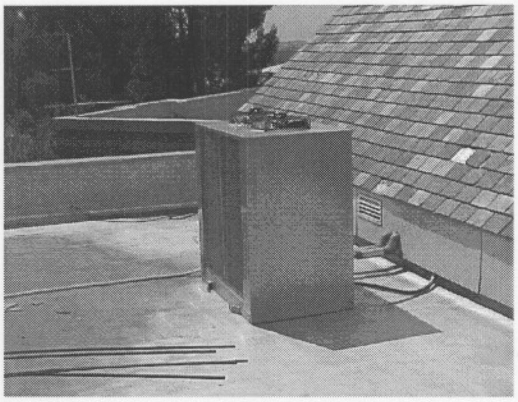


Figure 5: Heat pump unit installed at the hotel in case study 1

Figure 6 shows the measured typical daily peak demand profile of the heat pump, the in-line electrical resistance heater as well as the total hotel complex after the retrofit. The figure shows that around 14:00 when the peak demand is registered the rest of the hotel complex excluding water heating contributes 144 kVA. Although peak demand is registered at a different time, the 144 kVA for the rest of the building corresponds well with the 149 kVA obtained before the retrofit. However, the peak demand of the water heating installation now does not coincide with the building peak demand and only contributes 17 kVA instead of the previous 130 kVA during the building's maximum demand. This represents a reduction of 86 % in the peak demand contribution of the water heating installation.

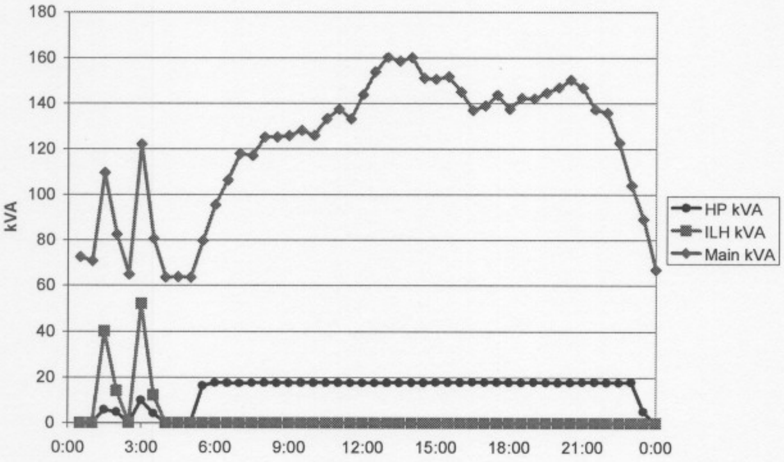


Figure 6 – Typical kVA demand after retrofit installation in case study 1

Case study 2

Figure 7 shows the measured typical daily peak demand profile of the water heating installation as well as the total hotel complex before the retrofit, for case study 2. Similar to the first example the peak demand of the water heating installation coincides with that of the building complex and contributes directly to the maximum demand of the building. At 8:30 when the maximum demand is registered, the water heating installation contributes 53 kVA and the rest of the hotel complex 61 kVA.

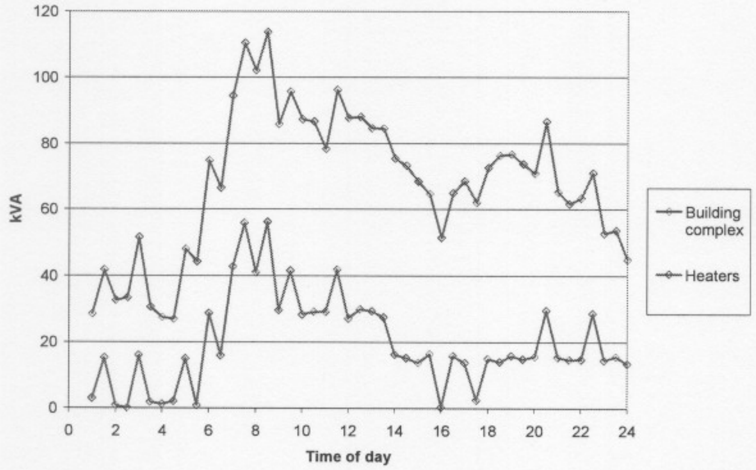


Figure 7: Typical kVA demand before the retrofit installation in case study 2

The retrofit installation included the installation of a 16 kW heat pump, and a 27kW in-line electrical resistance heater. The installed heat pump unit is shown in Figure 8.

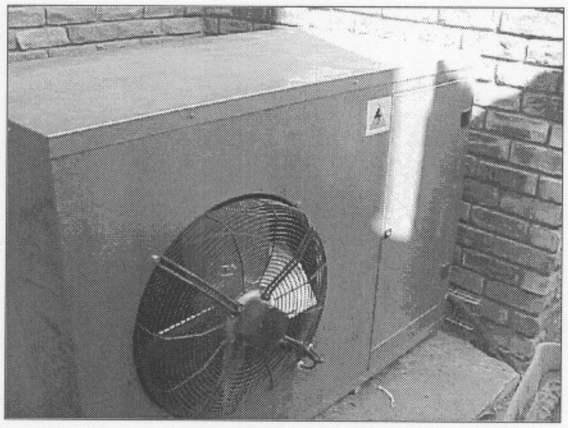


Figure 8: 16kW heat pump unit installed at the hotel in case study 2

Figure 9 shows the measured typical daily peak demand profile of the heat pump, the in-line electrical resistance heater as well as the total hotel complex after the retrofit. The figure shows that the building peak demand is registered at 18:30. At this time the hot water system contributes 7 kVA and the rest of the building 60 kVA. This represents a reduction of 87% in the peak demand contribution of the water heating installation.

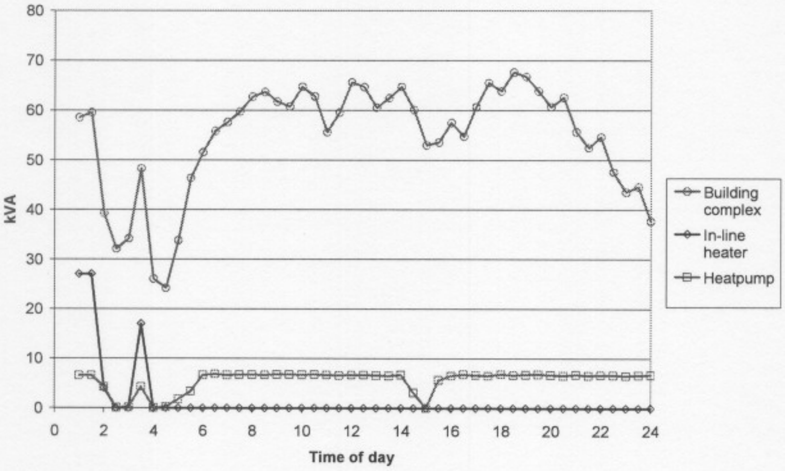


Figure 9: Typical kVA demand for retrofit installation in case study 2

Case study 3

Figure 10 shows the measured typical daily peak demand profile of the water heating installation as well as the total hotel complex before the retrofit, for case study 3. The peak demand of the building is registered at 8:00. At this time the water heating installation contributes 108 kVA and the rest of the hotel complex 134 kVA.

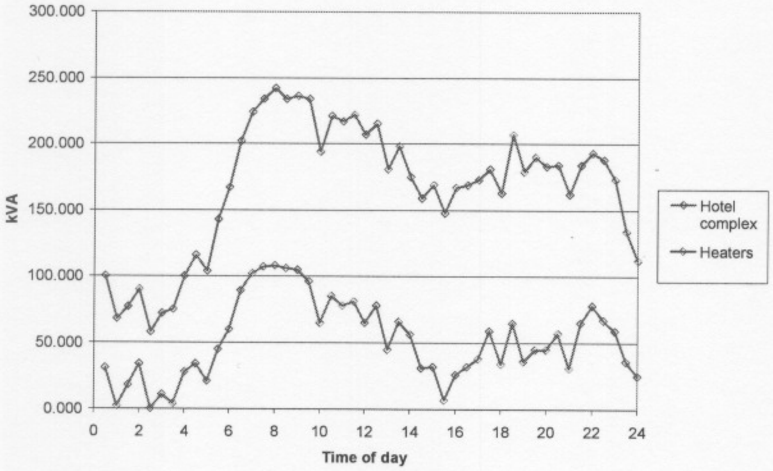


Figure 10: Typical kVA demand before the retrofit in case study 3

The retrofit installation included the installation of a 40 kW heat pump, and a 72 kW in-line electrical resistance heater. The installed heat pump unit is shown in Figure 11.

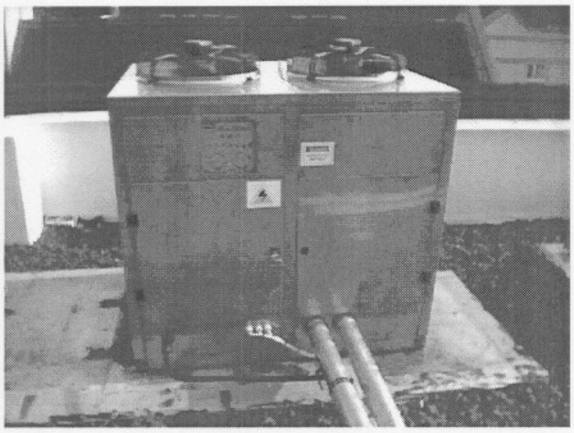


Figure 11: 40 kW heat pump unit installed at hotel in case study 3

Figure 12 shows the measured typical daily peak demand profile of the heat pump, the in-line electrical resistance heater as well as the total hotel complex after the retrofit. The figure shows that the building peak demand is registered at 19:30. At this time the hot water system contributes 17 kVA and the rest of the building 143 kVA. This represents a reduction of 84% in the peak demand contribution of the water heating installation.

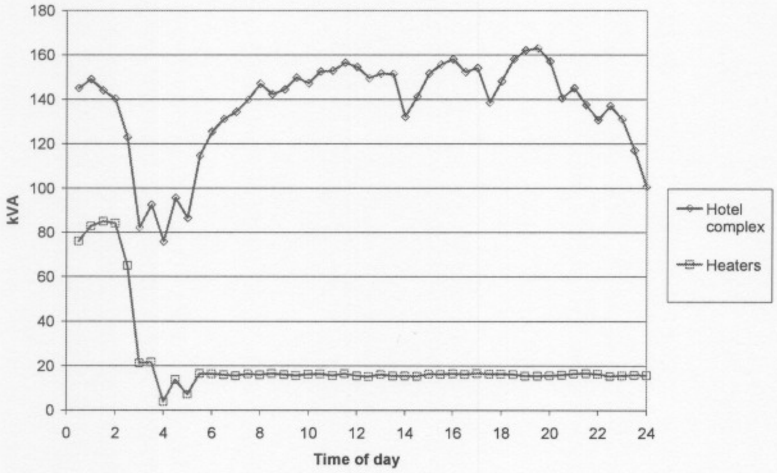


Figure 12: Typical kVA demand after the retrofit installation at case study 3

Table 2 provides a summary of the peak demand reduction achieved in the three case studies so far. The values shown represent an average value of all measured data. The typical uncertainty fractions associated with the results are shown in square brackets (Refer to Appendix C for uncertainty calculations).

Table 2: kVA reductions for three case studies, including uncertainty factors [u(kVA)/kVA]

	Measured kVA contribution before	Measured kVA contribution after	kVA demand reduction (% reduction) [u(kVA)/kVA]
Case study 1	128	17	111 kVA (86 %) [0.58%]
Case study 2	53	7	46 kVA (87 %) [0.58%]
Case study 3	108	17	91 kVA (84 %) [0.6%]

4.2 Measured energy consumption reduction

The improvement in energy efficiency obtained by the heat pump installation is analyzed in this section for case study 1. For purposes of comparison, measurements for one full month will be compared for the plant before the retrofit and after the retrofit. However, due to time constraints the measurements before and after the retrofit could not be conducted during the same month of the year for consecutive years. The results for the case before the retrofit were obtained during August 2002. The results after the retrofit were obtained during March 2003.

In order to account for seasonal changes that may influence the heat losses to the outdoor air, the measurements obtained in August 2002, before the retrofit, were adjusted to correspond to outdoor air temperatures for the month of March 2003. This was based on heating degree-days obtained from the actual measurements, using the CUSUM method (BRECSU (1993)). Furthermore, in order to account for the difference in actual water consumption during the two measurement periods, the electrical energy is further adjusted by means of the calculated COP of the specific system, so that the total useful thermal energy provided to the occupants in the form of hot water was in both cases equal to 21,854 kWh.

Figure 13 shows a comparison of the measured power consumption profiles after adjustments, during the course of a typical month, before and after the retrofit. From Figure 7 it is clear that a substantial reduction in energy consumption was obtained.

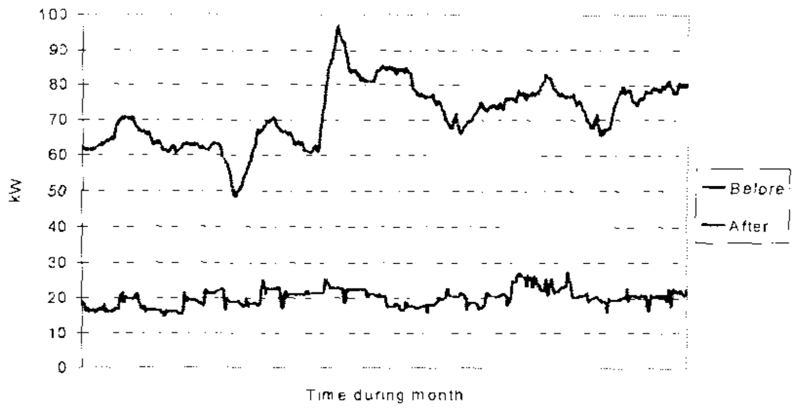


Figure 13 – Comparison between power consumption before and after retrofit

Table 3 provides a summary of the kWh savings achieved in the three case studies so far. The values shown represent an average value of all measured data. The typical uncertainty fractions associated with the results are shown in square brackets (Refer to Appendix C for uncertainty calculations).

Table 3: kWh reduction summary for three case studies, including uncertainty fractions [u(S)/S]

	Monthly kWh before	Monthly kWh after	kWh reduction [u(S)/S]	% reduction
Case 1	53600	15400	38200 [±2.67%]	71%
Case 2	11300	4400	6900 [±3.13%]	61%
Case 3	28200	10200	18000 [±2.99%]	64%

4.3 Hot water availability to building

A very important prerequisite when evaluating the hot water system retrofit is whether hot water supply to the building has not been compromised. Any peak demand and energy consumption improvements obtained by the retrofitted system should not be gained at the expense of hot water availability.

Figure 14 shows the typical hot water supply temperature of the conventional heating system before the retrofit, for case study 1. It can be seen that as the hot water consumption increases during the day, as was shown in Chapter 2 for hotels, the hot water supply temperature drops due to the mixing effect of the in-tank heaters. Hot water supply temperature is however sufficient throughout the day, since a large heating capacity is available to avoid temperature deficiencies.

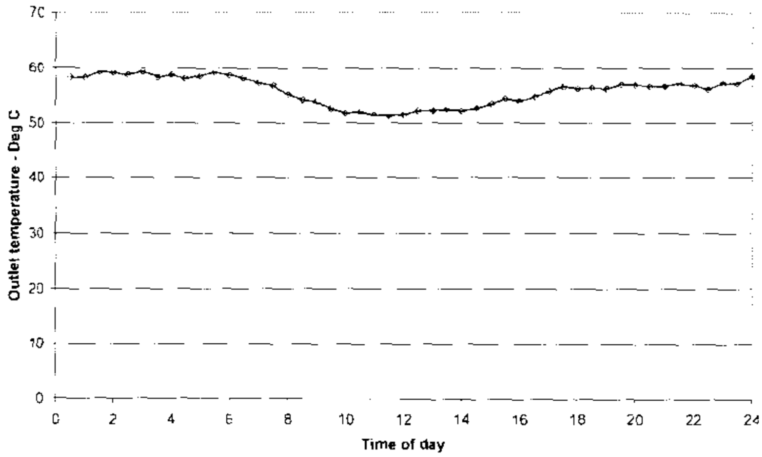


Figure 14: Typical hot water supply temperature of the conventional heating system before the retrofit

Figure 15 shows the typical hot water supply temperature to the building for the in-line heat pump system, for case study 1. Even though the installed heating capacity of the system has been decreased significantly, the hot water supply temperature is improved when compared to the conventional heating system. This is due to the stratified manner in which the heat pump and electrical in-line heater supply hot water to the storage tanks, as described in Section 2.2. In this case, the hot water supplied to the building never dropped below 55°C, compared to 52°C before the retrofit. Although the difference is not significant, it clearly illustrates that hot water supply is not compromised by the reduced heating capacity of the in-line heat pump system. Similar results have been obtained at the second and third case studies and are therefore not shown.

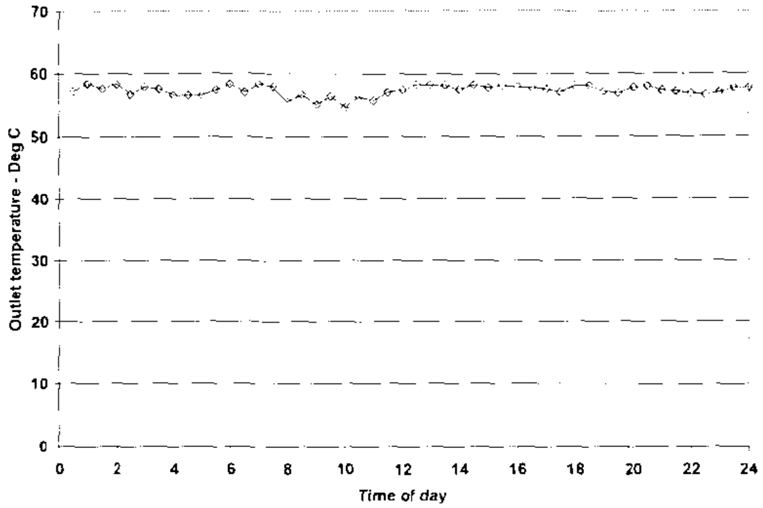


Figure 15 – Typical hot water supply temperature for the in-line heat pump system

4.4 Monthly savings for building owner and payback periods

From the previous three sections, it is clear that the improved in-line heating configuration combined with a heat pump proves to be very effective in terms of both peak demand and energy consumption reduction. Hot water supply temperatures are also improved. This type of installation is however significantly more expensive than a conventional in-tank heater installation. It is therefore important for a building owner to know exactly what his monthly savings will be, and how these savings will pay back the initial capital layout of such an installation.

Table 4 shows the typical straight payback period obtained by the building owners in the three case studies, as well as the internal rate of return based on a conservative 10-year life cycle.

Table 4: Straight payback period and IRR for the three case studies

	Straight payback period	IRR
Case 1	**12.5 months**	97.2 %
Case 2	**15.7 months**	76.5 %
Case 3	**24 months**	49.3 %

In the South African commercial sector straight payback periods of up to 36 months are normally acceptable, meaning that all three resultant payback periods are much better than the accepted standard.

4.5 Cost per thermal kWh compared for different types of installations

An interesting way of presenting the cost savings is the comparative cost per thermal kWh consumed by the building occupants, for the different water heating systems. The standard with which this is determined is as follows.

- Determination of the monthly thermal energy consumed by the building, as a function of the water consumption, inlet and outlet temperatures and specific heat capacity value.
- Determining the cost per kWh, by dividing the total monthly cost for the installation by the total thermal kWh consumed. The total monthly cost consists of both the peak demand costs and energy consumption cost.

Figure 16 shows comparative cost per kWh thermal energy before and after retrofit for all three installations. An operational cost reduction of 76-80 % is achieved for all the case studies.

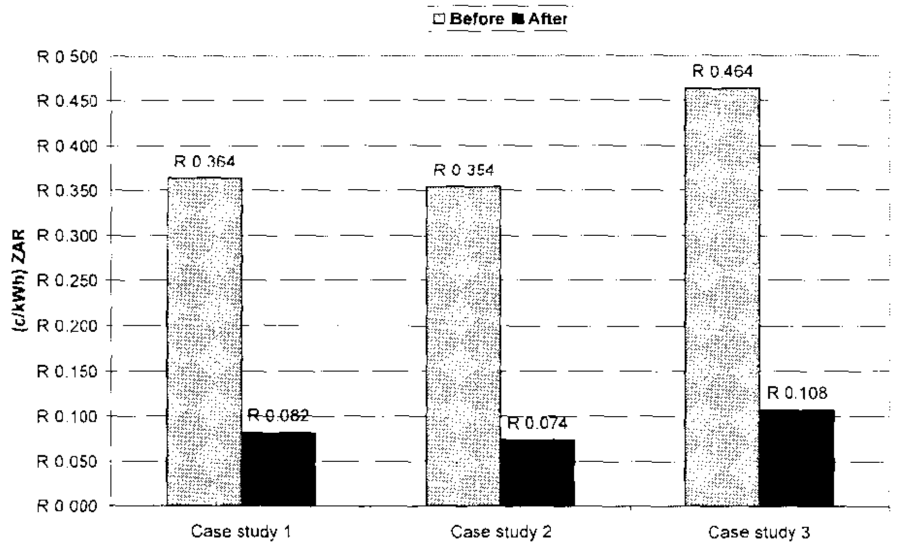


Figure 16 – Comparative cost/kWh before and after retrofit

5 Conclusion

Heat pump water heaters have penetrated only a fraction of the commercial water heater market in South Africa. The main reason for this is poor design practice, which leads to poor economics and high overhead cost per kW of installed capacity needed. This demonstration project shows that if integrated correctly with the rest of the installation via the improved in-line heating methodology, the economics of heat pumps are greatly improved. This can significantly increase the market for heat pump water heaters in South Africa.

If the in-line heating methodology, combined with heat pumps, is used to its fullest potential, it can lead to a total peak demand reduction of 108 MW in the commercial building sector. This represents 18% of the peak load reduction target set by ESKOM until the year 2015. It also represents an avoided cost of approximately MR 324 (ZAR) to ESKOM (Rousseau *et al* (2000)). The benefit to building owners is a significant saving in the monthly operational costs of the building, leading to improved viability for DSM projects in the South African commercial sector.

CHAPTER 4 - DEMAND SIDE MANAGEMENT FOR INDUSTRIAL RESIDENCE WATER HEATING SYSTEMS USING AN IN-LINE WATER HEATING METHODOLOGY

Abstract

This chapter illustrates the application of the improved in-line water-heating concept in an industrial DSM project, aimed at reducing the peak electrical demand associated with large sanitary water heating plants. The technology was successfully implemented on several real-life plants. Measurements from a selection of these plants are provided to illustrate that significant load reductions are achieved during the utility critical period between 18:00-20:00. The measured results also show that the peak load reduction is achieved without adversely affecting the availability of sufficient hot water to the building occupants. A very good correlation also exists between these measured results and simulations that were done beforehand to predict the DSM potential of the project.

The in-line heater concept provides an improved solution for DSM at sanitary water heating systems due to the stratified manner in which hot water is supplied to the tanks. This provides an improved hot water supply to users when compared to conventional in-tank heating systems, even with load shifting being done. It also improves the storage efficiency of a plant, thereby allowing the available storage capacity of a plant to be utilized to its full extent for DSM purposes.

1 Introduction

As part of ESKOM's DSM implementation initiative, the need was identified to shed as much as possible of the peak load imposed on the national electricity supply grid between the hours of 18:00 and 20:00 daily, especially during wintertime. As discussed in Chapter 1 of this thesis, ESKOM funded projects are currently aimed at the industrial sector where bigger impacts in terms of load shifting can be achieved. This chapter illustrates the application of the improved in-line water-heating concept in an industrial DSM project aimed at reducing the peak electrical demand associated with large sanitary water heating plants. The author was responsible for the successful implementation of the technology on several real-life plants at AngloGold Ashanti mine residences. This project was funded by ESKOM and completed in partnership with IST Otokon and M-Tech Industrial (Pty) Ltd.

In Chapter 2 hot water consumption patterns in industrial residences such as those found in the mining sector were analyzed and discussed. The influences that these profiles will have on system design were also determined with the aid of a simulation, with results presented for the conventional in-tank heating configuration typically found at these residences. As stated in Chapter 2, a yearly average of 81 liters of hot water at 60°C is consumed per person per day. The DSM project completed at the AngloGold Ashanti mines included water-heating facilities that serve a total of 13000 residents. The 13000 occupants therefore consume a total of 1.05 Million liters of hot water on average per day. This roughly represents a total of 57 MWh of energy consumed per day, not taking into account heat losses from the storage tanks, and taking the average inlet water temperature at 15°C. This is an average heating load of 2.4 MW per hour. Due to seasonal fluctuations in hot water consumption and inlet supply water temperatures, the average load present during winter should be even higher.

From the previous paragraph it is clear that the potential can exist for DSM projects aimed at reducing the load between 18:00–20:00 at these hot water facilities. This chapter takes a detailed look at the investigation process to determine the specific load between 18:00-20:00 at these hot water facilities, as well as the implementation of the in-line water heating methodology to achieve load reduction during this period.

2 Methodology

At present most of the water heating plant configurations in South African mining residences are based on the conventional in-tank configuration, as described in Chapter 3. A difference between commercial and industrial installations is however the installed capacity per person using the hot water facilities. Extensive surveys done as part of the DSM project discussed in this chapter, revealed that the installed heating capacity at these industrial facilities is typically 0.3 kW/occupant. This is less than 50% of the installed capacity per person typically found in hotels as mentioned in Chapter 3 (0.7 kW/occupant).

The in-line heating methodology, as proposed by Greyvenstein & Rousseau (1997) and described in Chapter 3 is now implemented at these water-heating plants. The benefits of the in-line heating methodology have been illustrated in Chapter 3 at hotels. There are however a number of differences in application between the commercial and industrial sectors:

- In Chapter 1, the difference between commercial- and industrial sector electrical tariffs is discussed. This leads to the installation of energy efficient heaters such as heat pumps in commercial buildings. In the industrial sector the emphasis lies purely on load shifting, and only electrical in-line heaters will be used.
- In the commercial sector the installed capacity of the in-line heater plant is reduced, since the system's demand contribution needs to be at a minimum throughout the day. In the industrial sector, the heating capacity will not be reduced. This allows as much as possible heating to take place during low price periods in the industrial tariff, which in turn allows more electrical load to be shifted out of the DSM- and high price periods.

Due to the above-mentioned reasons, an electrical in-line heater connected in the in-line heating configuration is installed at each of the plants. The heating capacity of each in-line heater equals the heating capacity currently installed at the existing plant.

3 Predicting the DSM potential between 18:00-20:00

In Chapter 2, Section 4, background is provided on a simulation program developed by Rousseau (Rousseau *et al* (2000)). This simulation model will be used in the following section to illustrate the differences in operation between conventional in-tank heating systems and the in-line heating configuration. Data from actual plants will be provided as input to the simulation program. The model is also used to determine the DSM potential for a plant. This is achieved by recording results for all of the 25 years simulated in the Monte-Carlo analysis, and calculating the average load present between 18:00-20:00 for the 25 years. This is done for a system operating during the DSM period, i.e. not controlled for DSM purposes, and for a system controlled during the DSM period. The difference in load can therefore be calculated as the DSM potential at a plant.

3.1 Illustrative example

An example of a typical plant found at the mine residences is used in this section to simulate the operation of such a plant. The need for retrofitting the plant to an in-line heating plant is also illustrated in this section.

The current plant specifications are as follows:

Installed storage tank capacity:	2 x 10000 liter (tanks connected in parallel)
Installed heating capacity:	2 x 120 kW in-tank heaters
Thermostat set-points:	60 °C.
Number of occupants served:	800
Average hot water consumption:	81 liters per person per day.

The hot water consumption profile determined in Chapter 2 for mine residences is provided to the simulation routine together with the current plant specifications. Figure 1 shows the simulated hot water consumption profile calculated by the simulation model for a winter's day, together with the average profile obtained in Chapter 2 that is provided as input to the program. By comparing the simulated profile with the average profile, it is clear how the statistical perturbation technique introduces the effects of uncertainties associated with the behavior of the occupants.

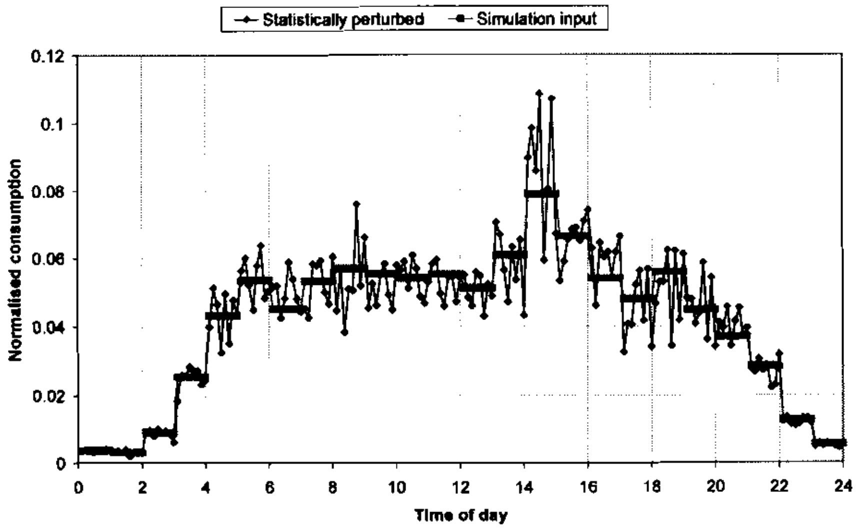


Figure 1: Statistically perturbed- and average hot water consumption profiles for a typical winter's day at the sample plant.

3.1.1 Current system operation

Figure 2 shows the hot water supply temperature for a winter's day at the sample plant. At this stage no load is being shed between 18:00-20:00. The hot water supply temperatures drop to as low as 41°C during and after the peak hot water demand period. This is caused by the fact that the rate of energy consumption from the storage tank is greater than the energy added by the heaters during this peak hot water demand period. Since the heating elements are situated near the bottom of the tank, the cold water that enters the system rapidly mixes with the remaining hot water. This is illustrated in Figure 3 since the temperatures at the top and middle of the reservoir are the same, with only the water at the very bottom of the reservoir below the heaters not being mixed with the rest of the tank.

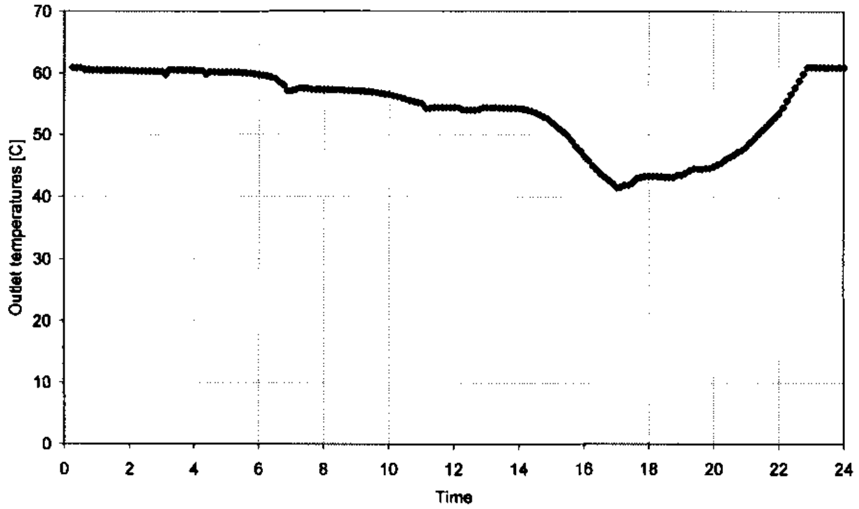


Figure 2: Hot water supply temperatures during a winter's day at the sample plant.

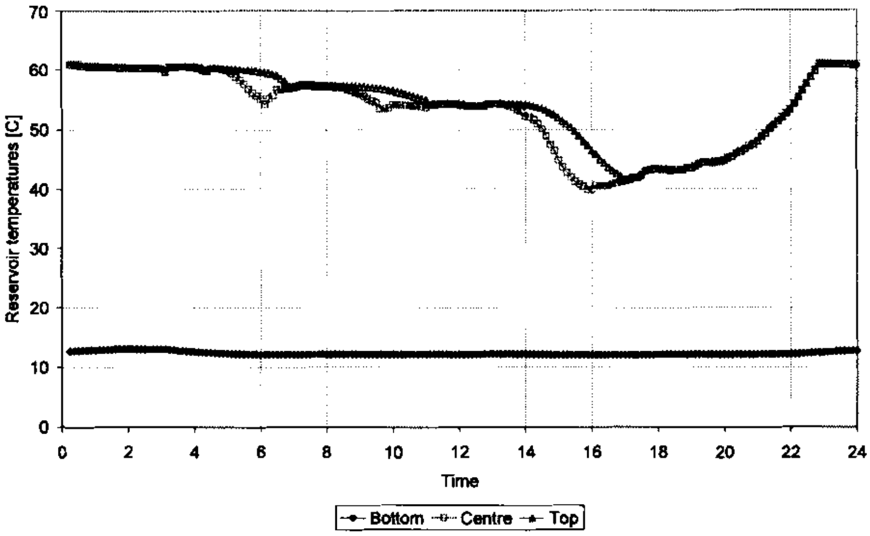


Figure 3: Simulated water temperatures at the bottom, centre and top of the reservoirs for the sample plant on a typical winter's day.

3.1.2 Current plant with the load shed between 18:00-20:00

In this section the current plant specifications are used in the simulation, but in addition the load is shed for DSM purposes between 18:00-20:00. Figure 4 shows the hot water supply temperature for a winter's day. The supply temperature drops to as low as 29°C in this case. This is to be expected, since the supply temperature already dropped to 41°C in the system without the load being shed. The hot water remaining in the storage tank is now consumed almost entirely during the load-shedding period.

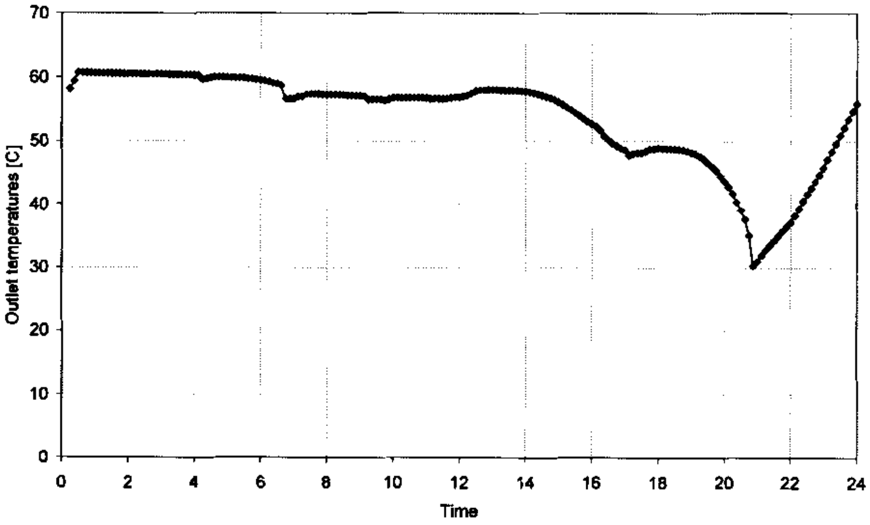


Figure 4: Hot water supply temperature during a winter day at the sample plant, with the load being shed between 18:00-20:00.

The temperature distribution in the tank is shown in Figure 5. A stratified temperature distribution appears during the load-shedding period. The stratification is however destroyed once the in-tank heaters are activated directly after the load-shedding period. This causes the temperature deficiencies to occur after the load-shedding period instead of during, and this lasts well into the evening.

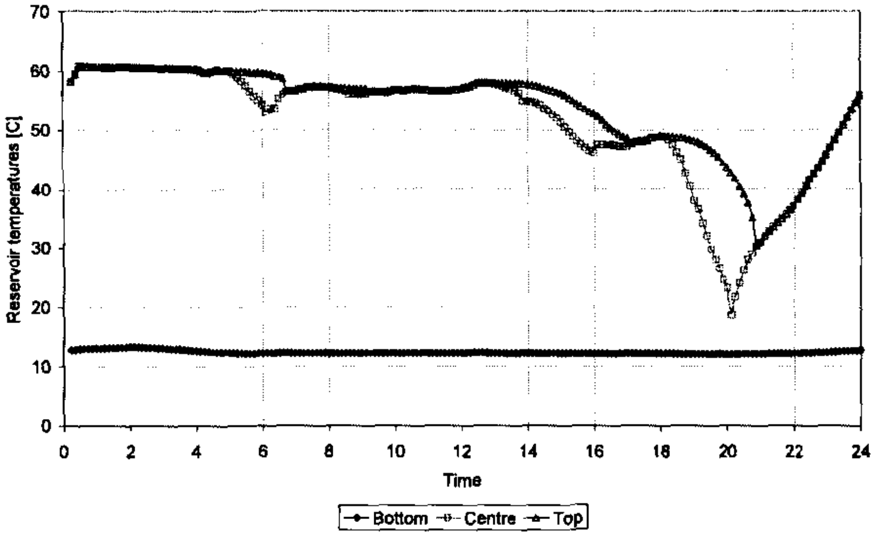


Figure 5: Simulated water temperatures at the bottom, centre and top of the tanks for the sample plant on a typical winter's day, with the load being shed between 18:00-20:00.

From this example, it is clear that the heating load cannot simply be shed with the current system layout, since it causes the hot water supply temperature to drop below 45°C for almost three hours in the evening. This is undesirable given the amount of hot water service demanded in this three-hour period. A different strategy is required to enable the load to be shed during the DSM period, but without a loss in hot water availability.

3.1.3 In-line heater plant with load shedding between 18:00-20:00

In this section the simulation is done for an in-line heater plant. The in-line heater plant specifications are as follows:

Installed storage tank capacity:	2x10000 liter (tanks connected in series)
Installed heating capacity:	1 x 240 kW in-line heater
Thermostat set-points:	50 °C at the bottom of the tank (Controls the in-line heater inlet temperature)
Flow control valve set point	60 °C (Controls hot water supply temperature)
Number of occupants served:	800
Average hot water consumption:	81 liters per person per day.

The simulation uses the same inputs for occupancy and hot water consumption profiles as in the previous sections. The load is controlled between 18:00-20:00 for DSM purposes. Figure 6 shows the hot water supply temperature of the in-line heater plant. Even with load control between 18:00-20:00 the temperature never drops below 50°C during a winter's day. This is achieved because the heater supplies the hot water to the top of the tanks. This means that even if the tank is filled with a large fraction of cold water, hot water is still available at the top. The activation of the heater after the load-shedding period therefore does not destroy the stratification, which would have decreased the hot water supply temperature. This is illustrated in Figure 7.

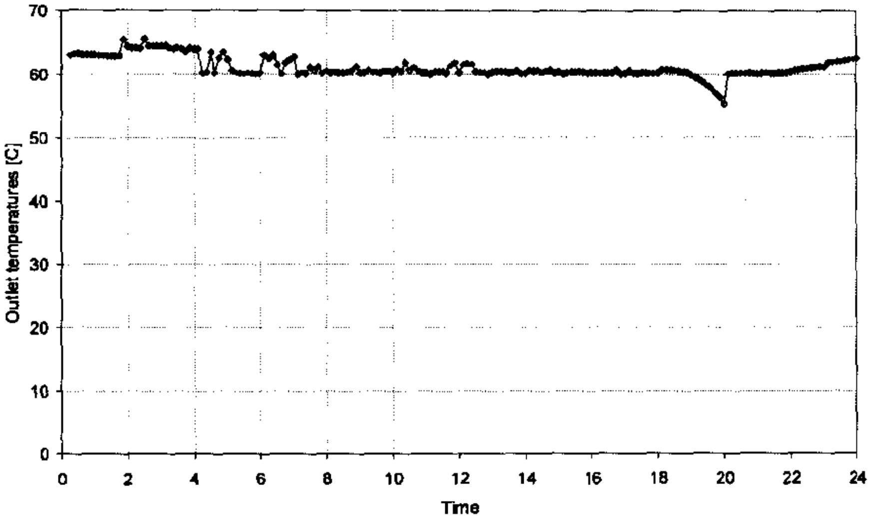


Figure 6: Hot water supply temperature of in-line heater plant.

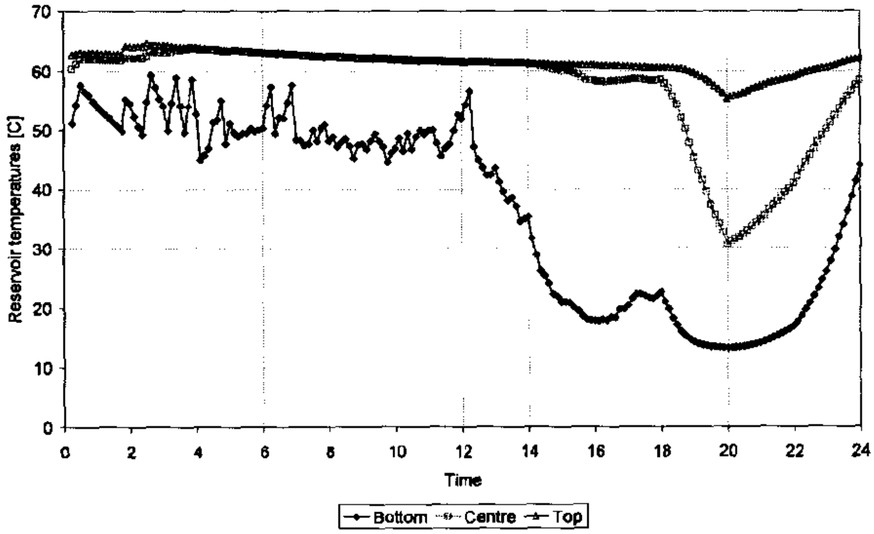


Figure 7: Simulated water temperatures at the bottom, centre and top of the tanks for the in-line heater plant on a typical winter's day.

To ensure that hot water supply to the users is maintained, a thermostat installed at a level 10% from the top of the storage tank will activate the in-line heater during the DSM period if cold water should ever reach this level. This type of control intervention is effective only because of the stratified manner in which hot water is supplied to the tank. In the case of in-tank heaters a thermostat installed near the top of the storage tank will not prevent hot water deficiencies, since the stratification will be destroyed once the heaters are activated. For example; if the hot water remaining in the tank is at 60°C and the cold water entering the tank is at 15°C, the mixed temperature after the in-tank heaters were activated by the top thermostat will be between 20°C - 30°C, depending on the rate of hot water consumption.

3.1.4 DSM potential between 18:00-20:00.

The Demand Side Management potential between 18:00-20:00 can be determined as the difference between the load required during this period before the retrofit, and the load required after the in-line heater retrofit. The simulated load required before the retrofit between 18:00-20:00 and for the rest of the day is shown in Figure 8. Data is presented as the maximum 60-minute integrated kVA demand for the given periods. It can be seen that a significant fraction of the installed capacity is activated during 18:00-20:00 each day in summer, and that almost the total installed capacity is activated between 18:00-20:00 during winter days. The annual distribution is function of seasonal variations in hot water consumption, inlet water and ambient temperatures.

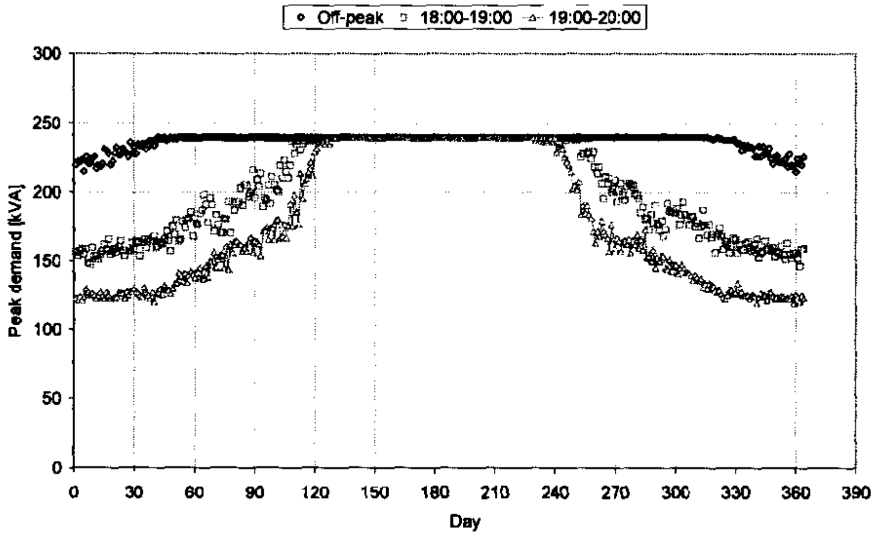


Figure 8: Load present before retrofit for each day of the year, shown for the periods 18:00-19:00, 19:00-20:00, and the rest of the day.

Figure 9 shows the simulated load required after the in-line heater system has been installed and the load has been controlled between 18:00-20:00. The load that was required before has been shifted out of the DSM period. The electrical load for the rest of the day (labelled "off-peak" in the graph) is now equal to the installed capacity for every day of the year, which was not the case before the retrofit (See Figure 8). This is caused by a cold-load-pickup of the hot water plant directly after the load-shedding period.

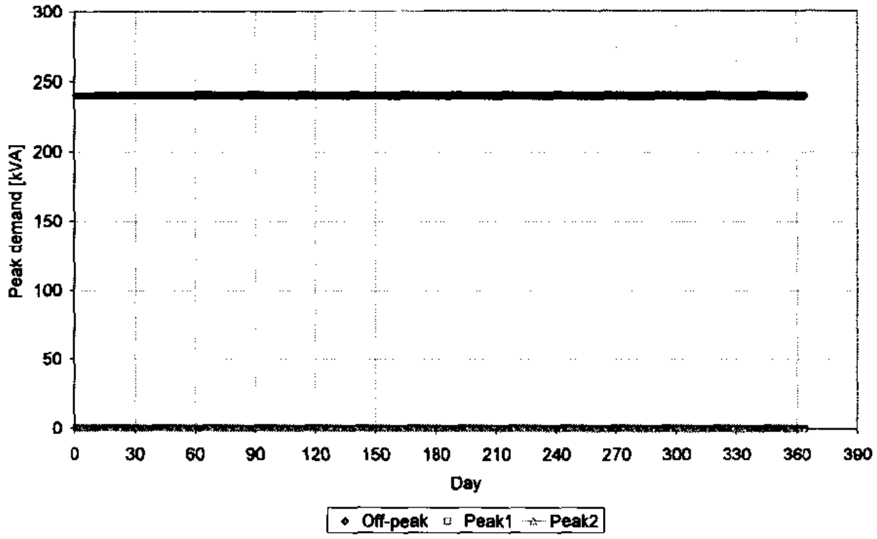


Figure 9: Load present after retrofit for each day of the year, shown for the periods 18:00-19:00, 19:00-20:00, and the rest of the day.

The DSM potential is now simply the difference between the 'before' and 'after' required loads. The simulation program calculates the monthly averages, and this is presented in Figure 10.

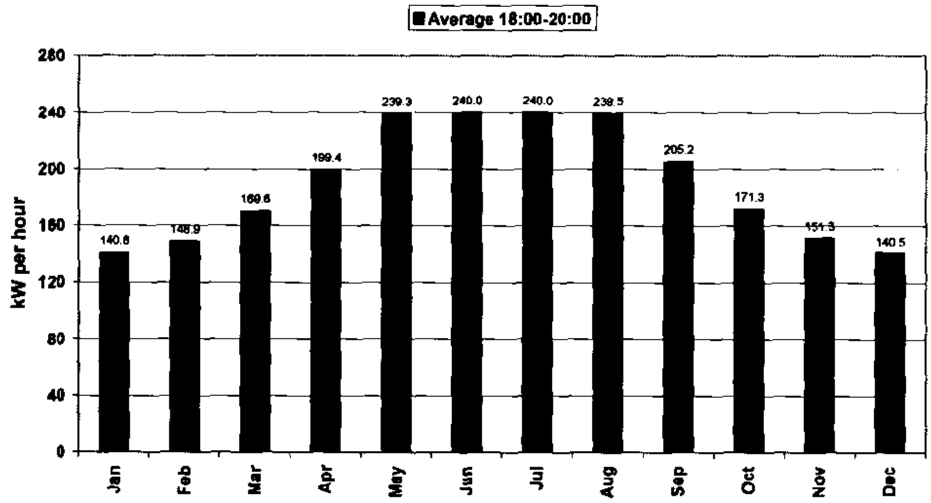


Figure 10: DSM potential for the plant presented as monthly averages

This method is now used to simulate all the plants relevant to this project. Figure 11 shows the simulated DSM potential summary for all of the 34 plants included in this project. The predicted DSM potential therefore varies between 1.84 MW in summer and 3.58 MW in winter.

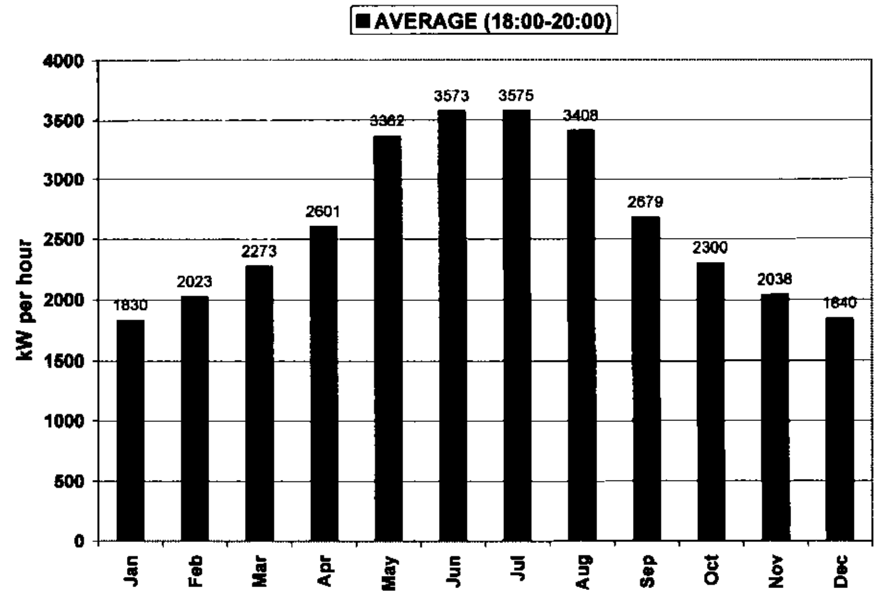


Figure 11: DSM potential summary of all 34 plants at the Anglo Gold DSM project.

4 Measured results

During the Anglo Gold DSM project 34 in-line heater retrofits were completed. All the installations vary in terms of usage, heating capacity and storage capacity. The in-line heating and demand side management methodologies used in all the plants are however the same. This section provides measured results from three individual installations, as well as a summary of the DSM impact realised by the completed project.

4.1 Determining the performance baseline of a system

The DSM impact delivered by each in-line heater system is determined as the difference between the electrical load present between 18:00 –20:00 before and after the retrofit. The typical load present before the retrofit can be measured, but is not necessarily representative of what the load would have been without a retrofit, based on current usage patterns. This is due to possible changes in hot water consumption patterns caused by different user totals or seasonal variations. This would lead to different electrical profiles than those measured beforehand. The measurements taken on the old systems are for this reason only used to develop a baseline model, which can be adjusted according to different usage patterns.

The method used in developing the baseline model is the Cumulative Sum (CUSUM) (BRECSU (1993)) method. This method essentially keeps account of all energy entering and exiting the system, and relates the electrical energy to the hot water consumption patterns and a certain heat loss load, by taking into account the temperature dead band of the system's control thermostat. The accuracy of this method is dependant on the size of the time steps used and the accuracy of input data, and does not necessarily provide an accurate result when short-term data is used. For longer periods when an average impact is required, the method does however provide acceptable accuracy. Since long-term impacts are required for the DSM projects, the method is suitable and is also used by ESKOM's Measurement and Verification (M&V) team (Van der Merwe & Grobler (2005)) to determine baseline performance.

4.2 Case study 1: 240kW In-line heater plant

The first case study is a 240kW in-line heater plant. The results presented are the average measured electrical power consumption profile over 30 days and also the calculated baseline profile. The baseline profile is based on the average measured hot water consumption profile for the 30-day period. The baseline calculation is verified by comparing the sum of electrical energy measured at the retrofitted plant to the calculated electrical energy of the baseline. This is a valid method since the energy efficiency was not changed at the plant, with electrical elements used in both in-tank and in-line configurations. The measurement period was 10 March 2005 to 9 April 2005. Figure 12 shows the average measured electrical profile vs. the calculated baseline profile. Data points represent the integrated load value for the following 30-minute period, i.e. the 18:00 data point shows the average electrical load for 18:00-18:30. It can be seen that a significant load shift is achieved between 18:00–20:00, with this load now added to the load already present in the period after 20:00. The baseline profile only deviated from the measured profile from 18:00 to 23:30. This means that the load shifted out of the 2-hour DSM took approximately 3½ hours afterwards to be restored. The average baseline load present between 18:00-20:00 before the DSM retrofit is calculated as 156kVA. Since the load was shifted completely out of the 18:00–20:00 period, a 156kVA load reduction was achieved at this plant.

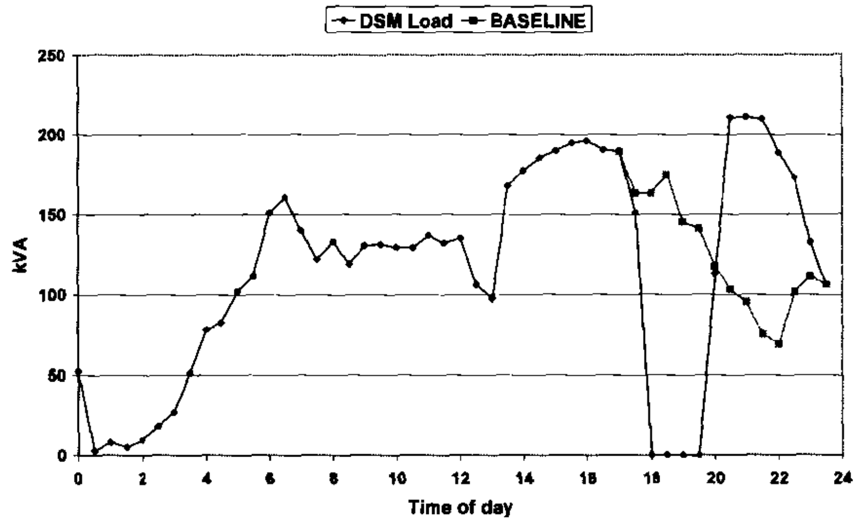


Figure 12: Average measured electrical profile vs. calculated baseline profile for the 240kW plant.

The fact that the load was shifted completely out of the DSM period means that the backup thermostat control as described in paragraph 3.1.3 was not utilized. This shows that the storage capacity available at this plant was sufficient to provide hot water to the users during the 2-hour DSM period.

The minimum required hot water supply temperature is 40°C, since the hot water is used for showering at a temperature of 37°C-40°C (ASHRAE (2003)). The 30-day measured hot water supply temperature is shown in Figure 13, providing both 30-minute interval average values and the 30-minute interval minimum temperature values. It can be seen that the hot water temperature never dropped below 43°C. This lowest temperature was provided to the users at the end of the DSM period. The hot water supply temperature increased to above 55°C once the in-line heater was activated again at 20:00.

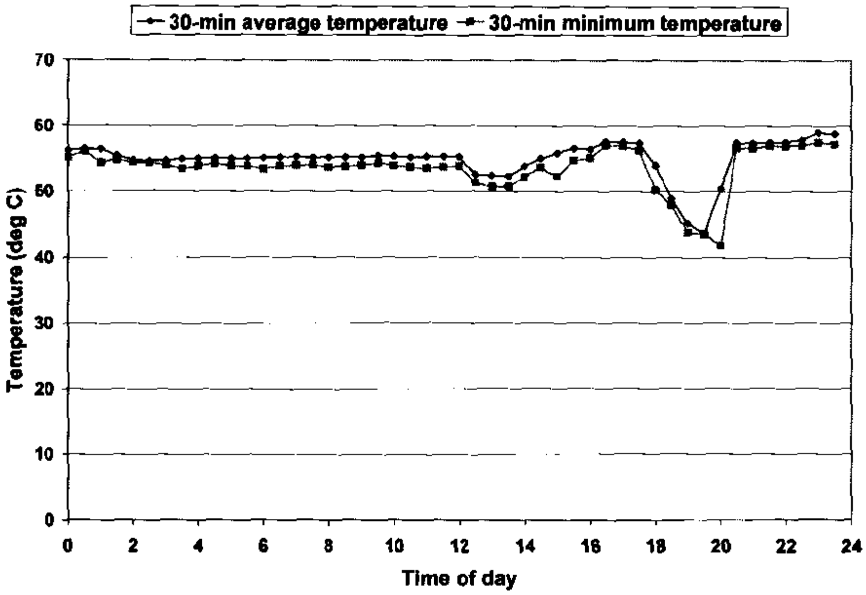


Figure 13: Measured 30-min hot water supply temperature for the 240kW plant.

4.3 Case study 2: 96kW In-line heater plant

The second case study is a 96kW in-line heater plant. The measurement period was 10 March 2005 to 9 April 2005. Figure 14 shows the average measured electrical profile vs. the calculated baseline profile. It can be seen that a significant load shift is again achieved between 18:00–20:00. The baseline calculation also shows that the total installed capacity would have been activated in the first DSM hour (18:00– 19:00). The average baseline load present before the DSM retrofit is calculated as 90kVA, which is a very high fraction of the installed capacity. Since the load is shifted completely out of the DSM period, a 90kVA load reduction is achieved.

In the first and second case studies no backup control was utilized during the DSM period. The third case study shows a scenario where the load cannot be shifted completely out of the DSM period. The in-line heater is in this case activated towards the end of the DSM period to avoid hot water supply deficiencies.

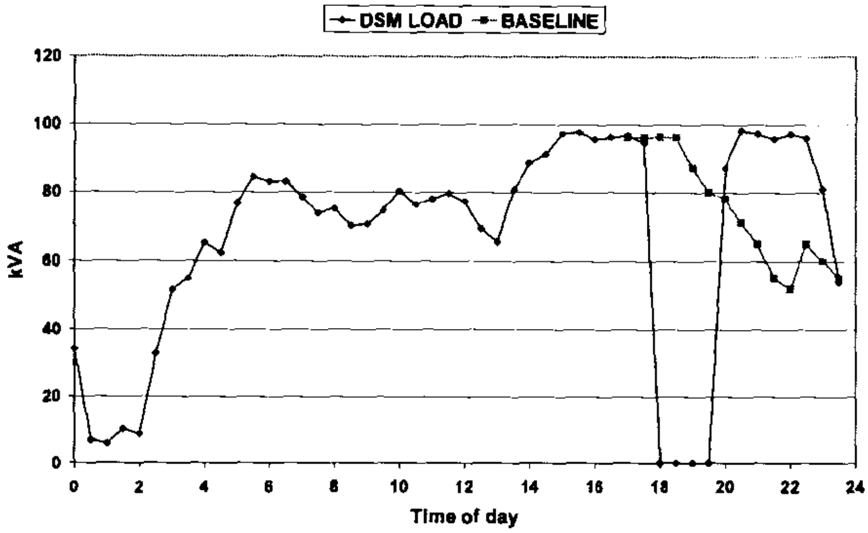


Figure 14: Average measured electrical profile vs. calculated baseline profile for the 96kW system.

4.4 Case study 3: 144kW In-line heater plant

The third case study is a 144kW in-line heater plant. The measurement period was 1 May 2005 to 31 May 2005, which is the start of the winter period in South Africa. As shown in Chapter 2, the hot water consumption increases towards winter and the hot water systems are therefore utilized more intensively. Figure 15 shows the average measured electrical profile vs. the calculated baseline profile. It can be seen that a significant load shift is achieved between 18:00–19:30, but that the heaters were in this case activated during the last 30-minute period between 18:00–20:00. 88kVA was measured in the period between 19:30-20:00, meaning that the heaters were activated at approximately 19:41, based on this load fraction present. This heater activation was caused by the hot water stored in the tanks being used up before the end of the DSM period. The backup thermostat control situated near the top of the storage facility as described in paragraph 3.1.3 activated the heaters to avoid hot water deficiencies. The average baseline load present before the DSM retrofit is calculated as 137kVA. With 88kVA consumed during 19:30-20:00, the average load present after the DSM retrofit is 22kVA. This results in 115kVA load shift being achieved at this plant.

The 30-day average and minimum hot water supply temperature is shown in Figure 16. It can be seen that the hot water temperature dropped to 40°C just before the heaters were activated in the period between 19:30–20:00. This complies with the overriding thermostat's set-point of 40°C. The hot water supply temperature increased almost immediately to above 50°C once the top thermostat activated the in-line heater. This illustrates the effectiveness of the in-line heating configuration combined with the backup thermostat control.

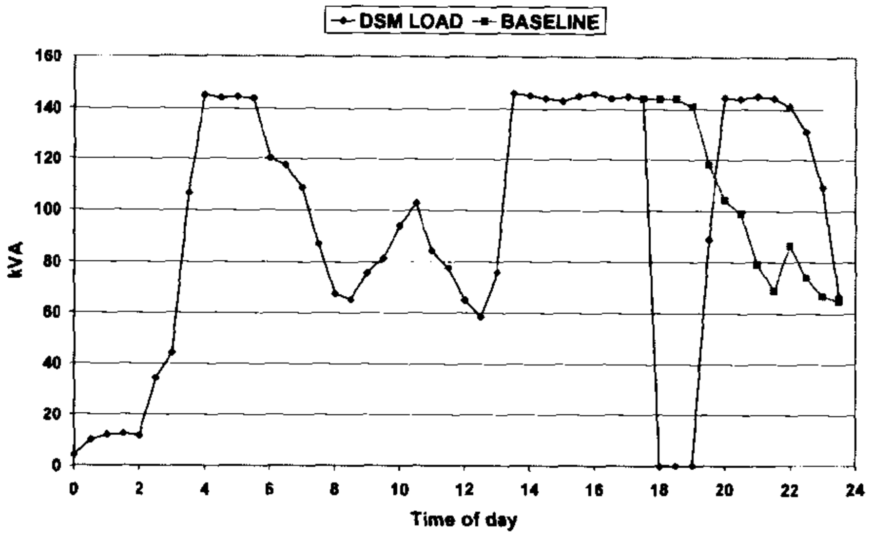


Figure 15: Average measured electrical profile vs. calculated baseline profile for the 144kW system.

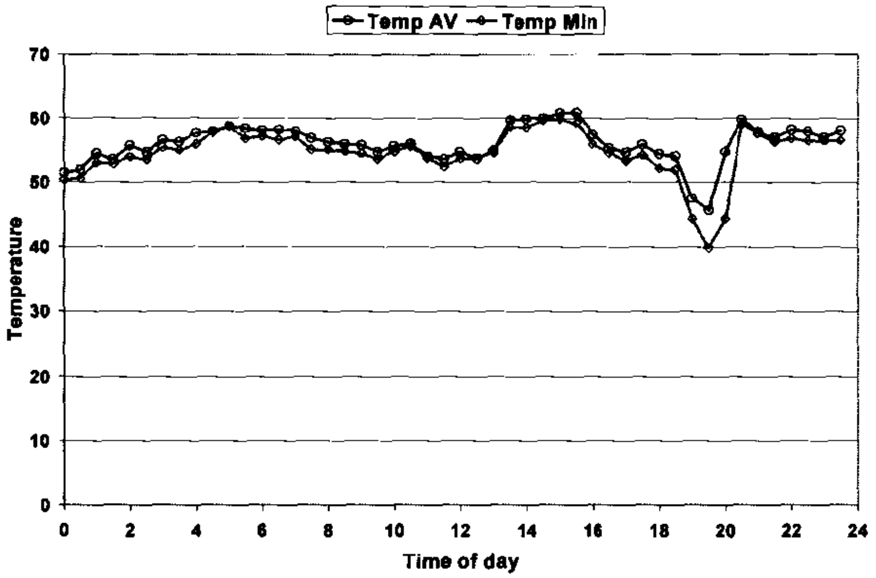


Figure 16: Measured 30-min average and minimum hot water supply temperature for the 144kW system.

4.5 Total DSM load shift achieved by the project during April 2005

This section provides the total DSM load shift achieved by the 34 retrofitted installations, for a 30-day period measured in April 2005. The results are presented in Figure 17. The sum of the measured electrical profiles for a month at the 34 installations is shown, together with the sum of the 34 calculated baseline profiles for the month.

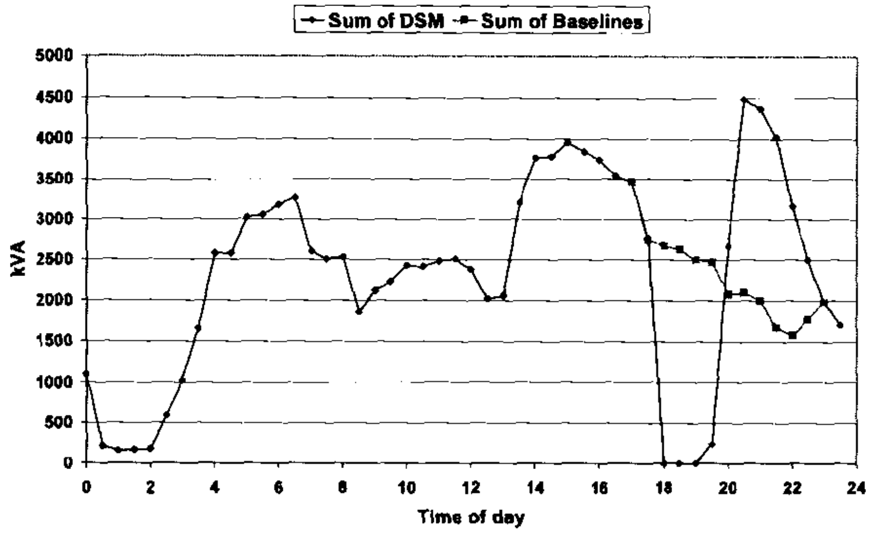


Figure 17: Average measured electrical profile vs. calculated baseline profile for all of the 34 plants

A total of 59 MWh was consumed on average per day by the 34 installations, for the month of April. The total hot water consumption was 1.027 Million liters at 60°C per day, which is 79 liters at 60°C per person. The total calculated baseline load during the DSM period is an hourly average of 2590kVA. This load was reduced after the DSM retrofits to an hourly average of 50kVA. The 50kVA was due to a load of 200kVA being measured at the sum of the retrofitted installations in the last 30-minute DSM period.

The total DSM load shift achieved during April was therefore 2540 kVA. This compares well with the predicted DSM potential of 2601 kVA as shown in Figure 11, with only a 2.4% difference between predicted and actual DSM potential. It should however be remembered that the actual DSM potential is also calculated as a function of the calculated baseline and measured DSM performance. The fact that a very good correlation exists between the simulated values and the CUSUM method provides confidence in the capability of both routines.

5 Summary of results

In summary, the in-line heater concept offers a number of advantages over conventional heating systems in terms of DSM capability. These advantages have been proven by measured results provided in this chapter, and are as follows:

1. The in-line heater concept improves significantly on the ability to supply hot water to users when the water-heating load is controlled. Hot water supply will be maintained even when the storage tanks are filled with a large fraction of cold water. This needs to be compared to conventional in-

tank heating systems where hot water will only be available to users several hours after the stored hot water was consumed. This effectively means that conventional in-tank heating systems cannot be used in a DSM project where electrical load needs to be shifted for several hours. By shifting load for a two-hour period in a conventional system, insufficient hot water supply can be caused for up to 3 hours, as shown by the simulation in section 3.1.2.

2. In the in-line heater concept, hot water is supplied in a stratified manner to the storage tanks. Not only does this provide improved hot water supply ability, but it also allows accurate backup control during the DSM period. The stratification allows a backup control thermostat to be installed near the top of the tank as described in section 3.1.3, which will re-activate the heaters just before the stored hot water is totally consumed. This means that the available storage capacity of a plant is utilized to its full extent without a loss in hot water availability. This was illustrated clearly by the third case study. In comparison, this type of control intervention in a conventional in-tank heating system would be ineffective. A stratified temperature distribution does appear when the in-tank heaters are not operational during a load-shedding period. This stratification is however destroyed by convection once the heating elements installed near the bottom of the tank are activated after the load-shedding period.

6 Conclusion

This chapter describes the successful implementation of the improved in-line heating concept developed by Greyvenstein & Rousseau (1997) into an industrial DSM project, aiming to achieve load shifting out of the utility critical period between 18:00-20:00. Measured results prove the concept to be working in practice. Good correlation was also obtained between measured results and simulations done beforehand to predict the DSM potential of the project. The in-line heater concept provides an improved hot water supply to users even with load control during the DSM period. The concept also significantly improves the storage efficiency of a plant, thereby allowing the available storage capacity of a plant to be utilized to its full extent for DSM purposes, without a loss in hot water availability.

The in-line heating concept provides a solution to the electrical utility and Energy Services Company when water-heating load needs to be reduced in DSM periods in the industrial sector. The concept can however provide further financial incentives to the client by reducing load in high price periods outside the DSM period as well. A control system that further optimizes the industrial in-line heater configuration to improve the cost efficiency of the system is evaluated in Chapter 7 of this thesis.

PART TWO

EVALUATION OF OPTIMIZED DESIGN AND CONTROL GUIDELINES FOR THE IN-LINE WATER HEATING METHODOLOGY IN THE COMMERCIAL AND INDUSTRIAL SECTORS

CHAPTER 5 - ELECTRICAL DEMAND AND THERMAL AVAILABILITY PREDICTION OF SANITARY WATER HEATING SYSTEMS BASED ON SIMPLIFIED FIRST LAW ANALYSIS

Abstract

Part one of the thesis discussed the status of hot water consumption patterns in hotels and mining residences. This was followed by chapters that described the application of the in-line heating methodology in both commercial and industrial DSM projects. A simulation program developed by Rousseau (Rousseau et al (2000)) was also used extensively in Chapter 2 and Chapter 4. This model allows long-term predictions of system operation via Monte-Carlo analysis. It provides a useful tool when the (DSM) potential of a water heating plant needs to be predicted as was done in Chapter 4.

A few shortcomings of the simulation program developed by Rousseau have however been identified that limits the potential for system optimisation studies. For this reason, a different demand prediction simulation model needs to be developed that will enable further research and optimisation of the new improved heating methodologies. This model needs to a) provide accurate results when calibrated for a specific system, b) once results are verified, provide a baseline for the verification of improvements and c) allow hot water systems to be optimised with the use of complex control algorithms. The objective of such an exercise is to provide optimal DSM and energy saving solutions without compromising hot water availability.

This chapter provides technical background and verification of such a simulation model developed for predicting the heating demand and hot water availability in sanitary water heating installations. A first law analysis is employed to account for the flow of energy in the water heating system. A simple three-node temperature distribution model is employed based on the assumption of thermal stratification. The verification study was done using measured data available from recent projects at several hot water installations, as described in Chapter 2 to Chapter 4. This data was used to evaluate simulation results for both mixed tank and stratified tank type systems. The results provide a high level of confidence in the demand and energy usage prediction capability of the model. The minimum hot water supply temperature and its time of occurrence were also predicted with high accuracy in the case studies.

This simulation model can now be used in optimisation studies for water heating systems. This will be addressed in Chapter 6 and Chapter 7 of this thesis for commercial and industrial applications respectively.

1 Introduction

Part one of the thesis demonstrated the status of hot water system usage patterns in both commercial and industrial sectors. The application of the in-line heating methodology in the commercial building sector was also discussed where heat pumps were utilised to obtain energy efficiency improvements. Finally the application of the in-line heating methodology in an industrial DSM project was demonstrated. These studies indicated that the potential for DSM exists in the commercial and industrial sectors, and that the implementation of the in-line heating methodology can exploit this DSM potential.

The need has however been identified in Chapter 1 to further refine and optimise the methodology for both commercial and industrial applications. To enable the evaluation of any optimisation proposals, a good electrical demand prediction model is required. This chapter describes the development and application of such a model that is based on simplified first law analysis. The new model aims to simplify the effort involved in obtaining accurate answers, and addresses several shortcomings found in previous models, making it more easily applicable for practical systems.

2 Previous work on thermal system simulation

Previous work on heat load forecasting (Arvastson (2001), Dotzauer (2002)) concluded that the outdoor air temperature and the social behaviour of consumers are the most important factors involved in demand prediction in general. In sanitary water heating systems this will be true as well, since the behaviour of consumers determine hot water consumption patterns while the outdoor air temperature will directly influence heat losses and supply water temperature. In high efficiency systems such as heat pumps and heat recovery systems, the outdoor temperature will also directly affect the performance of the heating plant (Abrams & Shedd (1996)). It is therefore of utmost importance to be able to simulate the influence of these parameters on the electrical demand of water heating systems. Given the complexity of the phenomena involved, computer analysis remains the most reliable method of demand prediction (Anzoategui (1996)).

A number of studies have been done on demand prediction for space-heating loads in buildings (Olofsson & Andersson (2001), Amjady (2001), Dotzauer (2002)). These models all predict heating demand as a function of the temperature difference between indoor and outdoor air. They make use of neural network technology to enable long-term demand forecasting using short-term measured data. Badescu (2002) provides first and second law analyses of heat pump operation for space heating purposes. The effect of thermal energy storage on both system operation and heat transfer losses is however not addressed in these studies.

For sanitary water heating systems, very few demand prediction models exist. This is mainly due to the stochastic nature of such systems. A number of deterministic storage tank simulation models do exist, although mainly used for predicting the efficiency of solar water heaters (Kleinbach *et al* (1993), Duffie & Beckman (1991), Klein (1976)). The Electric Power Research Institute (EPRI (1992)) provides two simulation programs namely HOTSIM and WATSIM. HOTSIM simulates the demand contribution and energy consumption performance of typical systems, without determining outlet temperature of the system. This shortcoming has been addressed within WATSIM, which also tracks the outlet temperature of the system and allows evaluation of economic performance. Both models can simulate a number of standard configurations and control methods. Unfortunately, modified configurations such as the improved in-line water heating system cannot be simulated. Furthermore, complex control algorithms can also not be simulated. The only variations allowed are adjustments to set points and the physical positioning of thermostats.

A simulation program developed by Rousseau (Rousseau et al (2000)) was used extensively in Chapter 2 and Chapter 4 of this thesis. This model allows long-term predictions of system operation via Monte-Carlo analysis, which is required when the long-term DSM potential needs to be predicted. The model has been verified using a laboratory test rig, and was found to provide an acceptable degree of accuracy in simulating systems based on both in-line and in-tank heating configurations. It makes use of a multi-node temperature distribution model, whereby the storage tank is divided into several control volumes for which mass and energy conservation are solved at each time-step. Although this model addresses the problem in some detail, it is quite complex and does not address the question of heat losses in a manner that is easily applicable in practice.

While comparing results from measurements on commercially operational plants (Rankin *et al* (2004)) with that of the model described above, the following shortcomings were identified:

1) The simulation model is unable to simulate the heat losses in the ring-main circulation system to an acceptable degree of accuracy. This is due to the fact that hot water outlets are opened and closed in a random manner at different positions along the ring main pipeline, which means that the flow rates and temperatures at different points change continually over time. Furthermore, in practice the pipe sizes and insulation thickness also vary widely and are often different from what is indicated on the original building plans. Therefore, the only way to predict ring main losses in practice is to correlate a lumped heat loss factor through experimental measurements of a specific ring main system.

2) The simulation model under-estimates peak demand contribution in periods of high water demand in some of the cases simulated. The activation of water heaters is controlled by thermostats, which under simulated conditions depend on the accuracy of the calculated temperature distribution in the storage tank. The possible reason for this error is therefore the difficulty in determining an exact temperature distribution in a multi-node temperature distribution model. Several heat transfer and de-stratification effects exist in hot water storage tanks, mainly due to the transient nature of water consumption in a building. The use of a complex temperature distribution model becomes rather inefficient under these conditions and can even lead to critical demand prediction errors.

3) The simulation makes use of complex heat transfer models, and can only take an average water consumption profile varied between established standard deviations as input. This eliminates the possibility of the model to be calibrated with measured data. The establishment of a base year simulation is of critical importance in verifying savings in any energy related project (Grobler & Den Heijer (2002), Heinemeier *et al* (1996), Anzoategui (1996), IPMVP (2002)). This requires the calibration of the model with system specific heat loss factors, which can only be obtained using measured data and general lumped heat loss factors.

4) The deterministic model is a valuable long term forecasting tool when only preliminary data is available for a specific water heating system, as was shown in Chapter 4. Large sets of data are however available now from the projects described in Part 1 of the thesis. This requires the development of a different model, which can accurately predict the heating demand with data obtained from the monitored systems.

The new model aims at obtaining accurate results for a specific system with large sets of data available. This is achieved by calibrating the model with system specific lumped heat loss factors. The new model also aims to improve the accuracy of demand prediction in periods of high hot water demand. Once a system simulation is calibrated to provide accurate and reliable results verified with measured data, the simulation could be used to improve on the operation of the specific system, or systems with similar heat loss characteristics.

A very important parameter in system optimization as described above is system availability. In a sanitary hot water system, availability is defined purely as the supply of hot water at a useful temperature to users. It should always be considered that hot water availability remains the primary concern for building managers. Any improvements made on the system operation should therefore satisfy temperature availability criteria first. For this reason the simulation model needs to be able to accurately predict the hot water supply temperature.

3 Development of the new simulation model

Due to reasons stated in the previous section, it was decided to develop a simulation routine for sanitary hot water systems, based on the following requirements:

1) The use of complex mathematical models to determine heat transfer losses should be avoided. Heat losses should rather be calculated based on calibrated lumped heat loss factors. These factors are determined by using the concept of heating degree-days to relate the heat loss factors to outdoor air temperature.

2) The behaviour of the whole system is modelled by using simplified first law analysis.

3) It should make use of a simplified temperature distribution model, which is a function of thermal stratification and the energy content of the storage tanks. This model should be able to predict the hot water supply temperature with good accuracy.

4) It should allow the input of long-term measured outdoor air temperature and water consumption profiles from monitored hot water installations.

5) It should include a flexible control algorithm, able to simulate most of the control methods for sanitary water heating systems. This includes standard thermostatically controlled systems with or without demand controllers, and time-of-use controllers able to respond to energy price fluctuations.

3.1 Theory

The first law of thermodynamics can be formulated on a rate basis, that is, at any instant there must be a balance between all energy flow rates, as measured in Joules per second (Watt).

The control volume of a hot water system is defined as the hot water storage tanks including the heating equipment, whether it is installed inside the storage tanks or outside the storage tank such as in-line heaters and heat pumps. Energy balance at any time *t* can be formulated as follows for the control volume:

$$\frac{dE}{dt} = \dot{E}_i - \dot{E}_e + \dot{Q} - \dot{L} \qquad [\,W\,] \qquad \textbf{Eq 1}$$

dE/dt represents the rate of heat gain of the control volume, while $\dot{E}_i$ and $\dot{E}_e$ are the rates at which thermal energy enters and exits the control volume respectively via mass flow. $\dot{Q}$ represents the rate of thermal energy that is generated within the control volume and $\dot{L}$ is the rate of heat losses from the control volume.

The first law must also be satisfied over any time interval Δt. When Eq 1 is integrated over a discrete time step Δt, the equation can be expressed in terms of *amounts* of energy entering, exiting and generated within the system during a time interval. If a change in the energy content within the control volume over time interval Δt is expressed as $E\text{-}E^0$, the energy balance can be obtained as follows:

$$E - E^0 = \dot{E}_i \cdot \Delta t - \dot{E}_e \cdot \Delta t + \dot{Q} \cdot \Delta t - \dot{L} \cdot \Delta t \qquad [\,J\,] \qquad \textbf{Eq 2}$$

To simplify the solution of the first law equation in the simulation model, an explicit solution is sought for Eq 2. This is required since all source terms are obtained using values from the end of the previous time-step. This will theoretically lead to a miscalculation of thermal losses and energy consumed during the time-step. The margin of error will depend on the size of the time-step and the ratio between the change in energy ($E\text{-}E^0$) and maximum energy content of the tank (E_{max}). If Δt is however kept small and ($E\text{-}E^0 << E_{max}$), the margin of error can be limited to an acceptable degree.

The energy balance during each time step is therefore calculated explicitly as:

$$E - E^o = \left(E_i^o - E_e^o + Q^o - L^o\right) \quad [\,\mathrm{J}\,] \qquad \textbf{Eq 3}$$

E represents the energy content of the storage tank at the current time step and E^0 the energy content at the previous time step. Q^0 represents the heat input from the water heaters during the time step, E^0_i - E^0_e the water consumption part of the load and L^0 the heat loss during the time step, which is dependent on the outdoor temperature at the end of the previous time step. A control algorithm determines the heat input according to a number of variables from the current and previous time steps.

Figure 1 shows a schematic of the basic approach followed during each time step of the routine. The energy content of the tank is a function of all the variables shown in Eq 3. The heat loss term L_0 consists of both standing heat loss from the storage tanks, and heat loss from the ring main system that circulates hot water through the building.

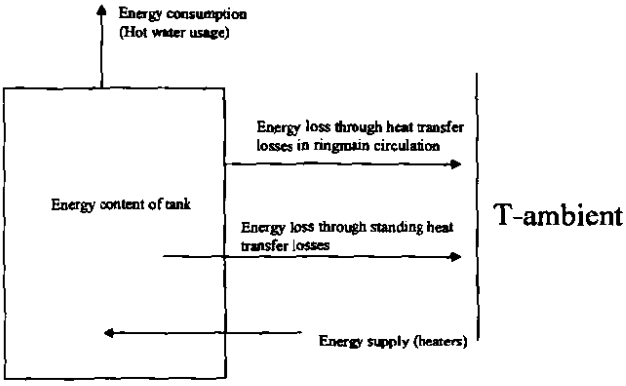


Figure 1: Energy balance during each time step

The energy content of the tank E is calculated as follows:

$$E = V_{total} \cdot c_p \cdot \rho_{water} \cdot \left(T_{storage} - T_{inlet}\right) \quad [\,\mathrm{J}\,] \qquad \textbf{Eq 4}$$

V_{total} represents the total storage volume of the tank, $T_{storage}$ the average water temperature in the tank at the time step, and T_{inlet} the inlet water temperature. Since E is determined in Eq 3, Eq 4 can be used to determine $T_{storage}$ which in turn will be used in heat loss calculations at the following time-step.

The amount of energy consumed during water take-off is calculated as follows:

$$E_e^0 - E_i^0 = V \cdot c_p \cdot \rho_{water} \cdot \left(T^0{}_{outlet} - T^0{}_{inlet}\right) \quad [\,\mathrm{J}\,] \qquad \textbf{Eq 5}$$

V represents the volume of water consumed during the time step, and $T^0{}_{outlet}$ the temperature of water supplied to the building at the previous time step.

The energy supplied by the heater during a time step is simply a function of the heating capacity of the heater and Δt in the case of an electrical resistance heater. If the heater is a heat pump, the energy supplied during a time step will be a function of the electrical input and coefficient of performance of the machine, and the time step Δt of the simulation. The coefficient of performance of the heat pump is determined as a function of the ambient wet bulb temperature, as will be discussed in section 3.3.

The typical energy loss through the ring main is a function of a preset temperature difference between ring main supply ($T_{rm,setout}$) and return ($T_{rm,setreturn}$) and water flow through the ring main (V_{rm}) during a time-step. The water flow is measured at the return to the storage tanks, after all water draw-off points on ring main piping. This preset value for energy loss will be representative of the average heat loss through the ring main, at an average temperature difference between ambient and ring main, for a specific system. The energy loss through the ring main specific to the previous time step (L^0_{rm}) is then related to the preset ring main loss using the concept of heating degree days (BRECSU (1993)). This relates the energy loss at the time step by comparing the temperature differences between ambient and ring main at the time step to that of the preset average temperature difference.

$$L^0_{rm} = V_{rm}\cdot\rho\cdot c_p\cdot\left(T_{rm,\,setout} - T_{rm,\,setreturn}\right)\cdot\frac{\left(T^0{}_{rm} - T^0{}_{ambient}\right)}{\left(T_{av,\,rm} - T_{av,\,ambient}\right)} \quad [\,J\,] \qquad \textbf{Eq 6}$$

T^0_{rm} represents the ring main temperature as an average of the outlet and return temperature at the previous time step, and $T_{av,rm}$ the average of the preset values for outlet and return temperature. Eq 6 shows that the loss factor will increase with a larger temperature difference between ambient and ring main water during the specific time-step.

The typical heat loss from the storage tanks will be expressed as a lumped fraction of the energy content of the storage tanks for each time step. This fraction represents the average heat loss from the storage tanks, at the average temperature difference between ambient ($T_{av,amb}$) and stored water temperature ($T_{av,storage}$). This heat loss fraction (k_{loss}) will be determined through measurements on typical systems. The heat loss specific to a time step ($L^0_{storage}$) will be related to k_{loss} by comparing the temperature difference between stored water and ambient for the time step and the average values for the system.

$$L^0_{storage} = k_{loss}\cdot\frac{\left(T^0{}_{storage} - T^0{}_{amb}\right)}{\left(T_{av,\,storage} - T_{av,\,amb}\right)}\cdot E^0 \quad [\,J\,] \qquad \textbf{Eq 7}$$

The average stored water temperature of a system is influenced by the system's usage patterns, and can therefore not be determined beforehand. The average storage temperature ($T_{av,storage}$) is for this reason given a guess value at the start of the simulation routine. At the end of a simulation cycle, a new guess value is calculated, and the simulation cycle is repeated until the guess value coincides with the calculation at the end of the simulation cycle.

3.2 Control Algorithm

The control algorithm used in the simulation routine allows several different methods of control, from as simple as thermostatic control, to time-of-use pricing optimisation control algorithms.

Thermostatic control

Most conventional water heating systems as well as the in-line water heating configuration employ a simple thermostat control method to control heating. Several thermostats can be used to control different stages of heating, with the thermostats placed at any non-dimensional height (h^*) in the storage tank. A definition of non-dimensional height is provided in Appendix A. Each thermostat normally has a dead-band incorporated into the design between switch-on and switch-off temperature.

The set-point values for each thermostat can be adjusted, including its dead-band value and position on the storage tank.

Analogue DSM controller with feedback

An analogue control system incorporating timers with thermostatic feedback provides load control on different levels is also included in the simulation model. Different timers can allow complete load shedding, partial load shedding or load boosting according to preset Demand Side Management criteria. Feedback from thermostats can be used to override load-shedding signals in the case of hot water deficiencies. The system can also be controlled via a demand control system measuring the building load that sheds the water heating load in an effort to reduce building peak demand.

The above-mentioned control methods are required to simulate the type of systems that are currently operational in the commercial and industrial sectors. This includes both conventional in-tank heating systems, and in-line heating systems as described in Chapter 3 and Chapter 4 of the thesis. Additional control methodologies will be developed and tested in Chapter 6 and Chapter 7.

3.3 Coefficient of performance of heat pump

Tests were performed on an in-line water heating heat pump utilizing a head pressure control valve as outlet temperature controller. Thermal performance was determined as a function of wet bulb temperature and inlet water temperature. It was found that the coefficient of performance (COP) is mainly dependent on wet bulb temperature, which determines the evaporating temperature within the cycle. This is a similar result when compared to previous studies measuring heat pump performance (Van Eldik (1999)). Only a slight dependency on the inlet water temperature is found, since the inlet water temperature only marginally influences condensation temperature in the cycle. Condensation temperature is primarily dependant on the outlet temperature, which in this case is fixed. Figure 2 shows a typical graph of COP vs. inlet water temperature and ambient wet bulb temperature.

Due to the complexity in determining the inlet water temperature in the simulation routine, it was decided to calculate the heat pump thermal output only as a function of ambient wet bulb temperature in the simulation routine. This again eliminates the need for a complex temperature distribution model able to simulate the inlet water temperature into the heaters. Comparison between the calculation of COP using wet bulb temperature and water inlet temperature, and calculation of COP using only wet bulb temperature reveals a maximum error of only 1.8%. This is acceptable in terms of the overall expected accuracy of the simulation routine.

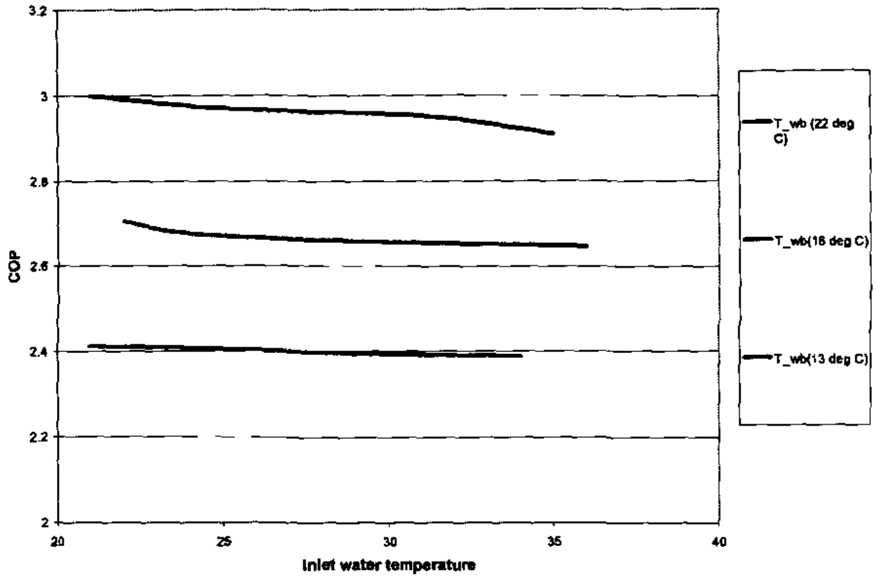


Figure 2: COP vs. wet bulb temperature and inlet temperature

3.4 Temperature distribution model

The simulation routine calculates the total energy content of the tank during each time-step. This means that an average water temperature in the tank will be known, as calculated by Eq 6. By assuming thermal stratification in the storage tanks, a simple three-node temperature model can be solved as a function of the total energy content of the storage tanks. The accuracy of such a model is however dependant on the level of stratification in the tank. This needs to be addressed first before such a model can be implemented.

Kleinbach *et al* (1993) and Rosen (2000) states the use of two criteria to determine the level of stratification in a storage tank namely: a) whether plume entrainment occurs or not, and b) the number of storage tank turnovers per day.

1. Plume entrainment - This occurs when the supply temperature drops below the temperature in the top of the tank. As a result, a downward-directed entrainment force will drive the incoming fluid down in the tank. Due to its turbulent motion and viscosity, the hot fluid in the tank will be entrained in the falling plume. Thus, the incoming stream is heated, and it will fall down to the

position in the tank where its density, and therefore temperature, matches that of the tank. The phenomenon is known is 'plume entrainment' and it will decrease the degree of stratification in the tank. Due to the stable temperature supply in the improved in-line heater concept, plume entrainment does not occur. For this reason the temperature distribution model need not include a plume entrainment model. In conventional in-tank heaters, this phenomenon cannot occur since hot water is not added at the top of the tank.

2. Tank turnovers - A general correlation is used by Kleinbach *et al* (1993) to determine the amount of mixing as a function of tank turnovers. Values of five tank turnovers or less (Q^*=>0.2) per daily mass removed is considered a low flow system, with associated low levels of mixing and de-stratification. All of the water heating systems discussed in Chapter 3 and Chapter 4 have sufficient storage capacity with $Q^*>0.2$. According to the correlation, these systems will be so-called 'low-flow' systems with associated high levels of stratification.

According to the above-mentioned criteria, the in-line heating systems simulated in the routine will have high levels of stratification, and therefore a simple temperature distribution model using only the average energy content of the storage tanks can be used.

Rosen (2000) proposes the use of a simple three-node, plug flow, temperature distribution model. The model consists of three horizontally uniform zones, which are vertically stacked. Temperature varies linearly as a function of height within each zone, and continuously across adjacent zone boundaries. This means that the temperature at the top of a zone then equals the temperature at the bottom of the zone directly above it. It is assumed that there are no horizontal temperature gradients in the tank. This has been determined by experimental work in previous studies (Pate (1977)). Figure 3 shows a schematic representation of the modelling approach. As the energy content of the tank changes, the size of the hot and cold temperature zones will vary. This means that the thermo cline region, or temperature transition zone between hot and cold water (Zone 2), will move up and down within the tank.

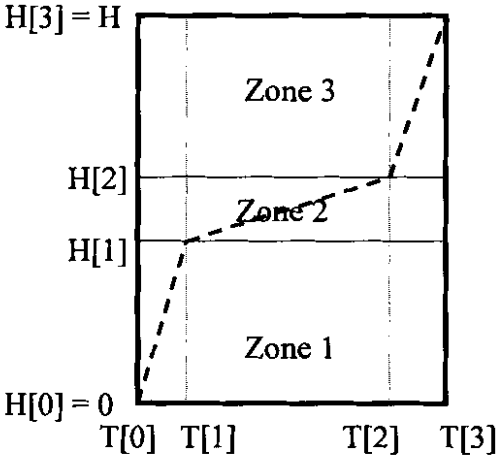


Figure 3: Three-node plug flow temperature distribution model

The vertical up and down movement of the transition zone will therefore control all tank thermostats. The model is solved by setting boundary conditions for the temperature variation within each zone, and for the size of the transition zone. With the size and temperature variation of the transition zone fixed, the energy content of the transition zone is a fixed quantity, if sufficient energy content is available in the tank. The sum of the energy content of all the zones are set to equal the total energy content, according to the principle of conservation of energy. The routine then calculates the size of hot and cold water zones in the tank and therefore the position of the transition zone in the tank. When the energy content of the tank falls below the fixed energy content of the transition zone, the hot water zone will simply be taken out of the equation, and the calculation will indicate that the transition zone is at the top of the storage tank. The same principle applies when the energy content of the tank is very high; the cold water zone will be taken out of the equation and the calculation will indicate that the transition zone is at the bottom of the tank. The low and high-energy content scenarios are illustrated in Figure 4.

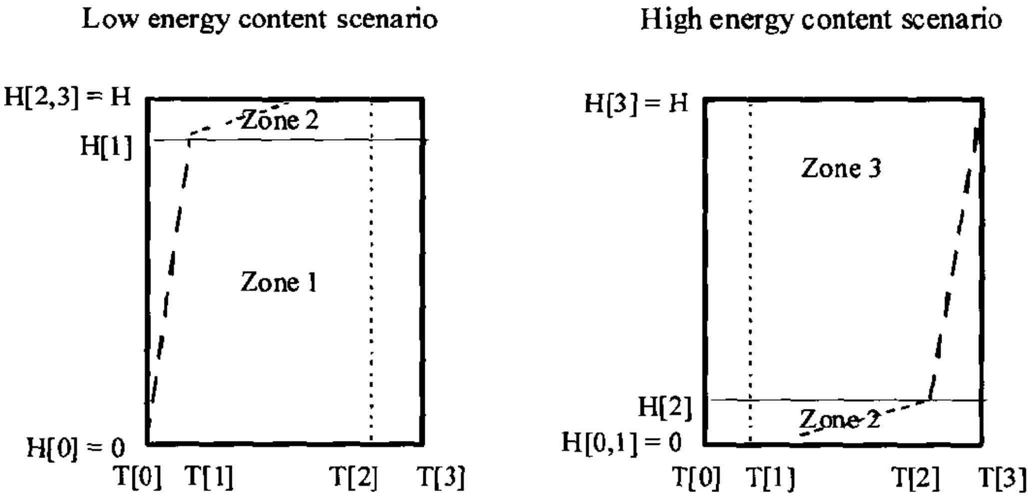


Figure 4: Low- and high energy content scenarios in the plug flow model

3.5 Calculation of outlet temperature

Outlet temperature in a conventional water heating system is a function of the energy content in the tank. This is due to the in-tank heaters continuously mixing the water inside the storage tank, as described in Chapter 3.

$$T_{outlet} = F(E) \qquad \text{Eq 8}$$

The only exception to Eq 8 occurs when the heating load is shed by the control algorithm. In this case a stratified temperature distribution will appear, with the outlet temperature not calculated as a function of the average tank temperature as in the mixed tank case. This stratification will however be destroyed once the heaters are activated again.

If the hot water is supplied into the building supply line at the top of the storage tanks at a constant temperature, as is the case with the improved in-line heating system, the outlet temperature will be a combination of the heater supply and the storage tank supply.

If the water consumption rate is lower than the rate of water supplied by the heaters ($m_c < m_{heater}$)

$$T_{outlet} = T_{heater,out} \qquad \text{Eq 9}$$

If the water consumption rate is higher than the rate of water supplied by the heaters ($m_c > m_{heater}$)

$$T_{outlet} = \frac{\left(T_{storage} \cdot \left(\dot{m}_c - \dot{m}_{heater}\right) + T_{heater,out} \cdot \dot{m}_{heater}\right)}{\dot{m}_c} \qquad \text{Eq 10}$$

with $T_{storage}$ determined by the temperature distribution model.

4 Input parameters

4.1 Water consumption profiles

The simulation routine will make use of data obtained from the monitored water-heating installations. These hot water systems are installed with a volumetric flow meter, as well as inlet and outlet temperature sensors, enabling the accurate tracking of hot water consumption over long periods of time. This data will be provided as input to the simulation routine.

4.2 Weather data

The International Performance Measurement and Verification Protocol (IPMVP 2002) states that government published weather data should be treated as the most accurate and verifiable. The accuracy of the data depends however on the actual location of the weather station, and the possible difference between the ambient conditions of the weather station and the actual installation site. The errors created by uncertainty in weather data are however generally treated as not being quantifiable, and therefore no confidence level or margin of error can be associated with weather data. Hourly data obtained from weather stations for dry and wet bulb temperature will therefore be used in the simulation routine. This weather data is obtained for the same periods as the data supplied from the measured water heating systems.

4.3 System specifications

The individual specifications of each system that will be simulated can be provided as input to the program, including the following:

Physical properties

The physical properties of the system are provided as inputs such as tank size, plant configuration, heater type and heating capacity.

Control algorithm

The control algorithm can be specified. This includes thermostat positions, set-points and dead band value. Time-of-use schedules and peak demand control settings can also be specified.

Heat loss characteristics

The typical heat loss characteristics can be specified as follows:

- Typical supply and return temperature, and flow rate for the ring main system.
- Typical lumped heat loss factor for standing heat losses from the storage tank, expressed as a percentage of the stored energy content relative to the average ambient temperature.

5 Verification of simulation routine: Prediction of electrical demand

The simulation routine is verified using data sets obtained from the monitored installations as described in Chapter 2 to Chapter 4. The results of the routine will be calibrated by changing the heat loss constant until the energy consumption converges to within 0.25% of the measured energy consumption. These specific heat loss constants will be recorded as the typical heat loss constant for this type of system, for future use in similar systems.

5.1 Simulation of an in-line heat pump water heating system

Data is now provided to the simulation routine from an in-line heat pump water heating system. This system is installed in a hotel in Johannesburg. Typical hot water consumption patterns for this hotel was analysed in Chapter 2. This system was also 'Case study no.3' in Chapter 3. The system specifications are provided in Table 1.

Comparison between simulation results and monitored data will be made by analysing the following.

1. Comparison between simulated and measured data for a) total electrical consumption and b) thermal energy production by the heat pump.
2. Directly comparing heating demand for three randomly selected 24-hour sample periods.
3. Comparing the recorded maximum demand for the month during peak and off-peak periods.

Table 1: Systems specifications used in simulation

Storage capacity	16000 litres
Heating capacity	Heat pump: 40kW @ 10°C Wb 2-stage electrical resistance in-line heater: 32kW + 16 kW
Plant configuration	All heaters connected according to in-line heating concept: Water supplied via temperature controllers to the top of the storage tank.
Set-point temp, dead band	58°C, 4°C
Heat pump control thermostat	Situated near bottom of tank, set point 53°C
Thermostat position, set-point	Electrical heater control Stage 1+2: Height 55% of total tank height, set-point 37°C
Off-peak timer	0:00 – 5:00: Electrical heater assisting heat pump during periods of low electrical demand in the rest of the building.
Low ambient signal	Calling stage 1 of back up heater to replace heat pump when ambient conditions drop below 4°C dry-bulb.
Water consumption	Period 17/11/2002 – 16/12/2002
Ambient conditions	Period 17/11/2002 – 16/12/2002
Load shedding device or demand controller	None

Electrical energy consumption and thermal energy production

Comparative figures for electrical energy consumption and thermal energy production are shown in Table 2.

Table 2: Electrical energy consumption and thermal energy production

	Electrical energy consumed	Thermal energy produced
Simulation	7885.0 kWh	17112.46 kWh
Measured	7882.6 kWh	16904.5 kWh
% Error	0.03 %	1.2 %

From Table 2 it can clearly be seen that the routine has been calibrated by changing the heat loss constant to match measured and simulated electrical energy consumption. The resultant heat loss constant is 0.64% of heat loss from the simulated storage tank energy content, relative to ambient temperature, per hour. The thermal energy produced by the heat pump is also predicted with good accuracy.

Comparison of 24-hour demand profiles.

Figure 5 to Figure 7 show demand profiles for three randomly chosen measurement periods, comparing simulation results and measured data. The data shown are 30-minute integrated 24-hour demand profiles for the heating equipment.

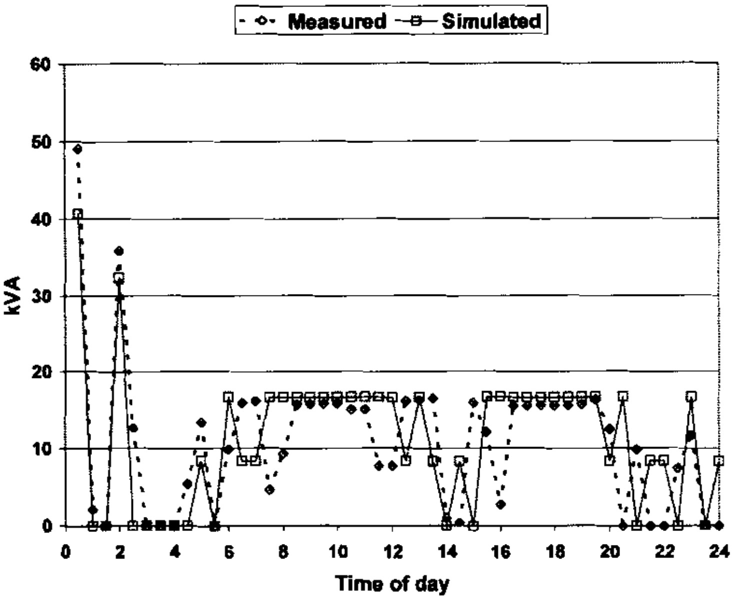


Figure 5: Comparison between simulated and measured data – 23/11/2002

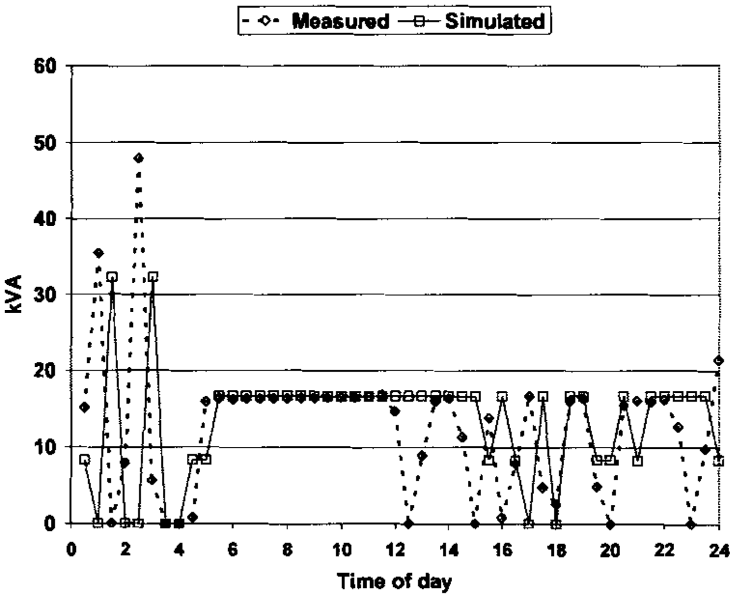


Figure 6: Comparison between simulated and measured data – 04/12/2002

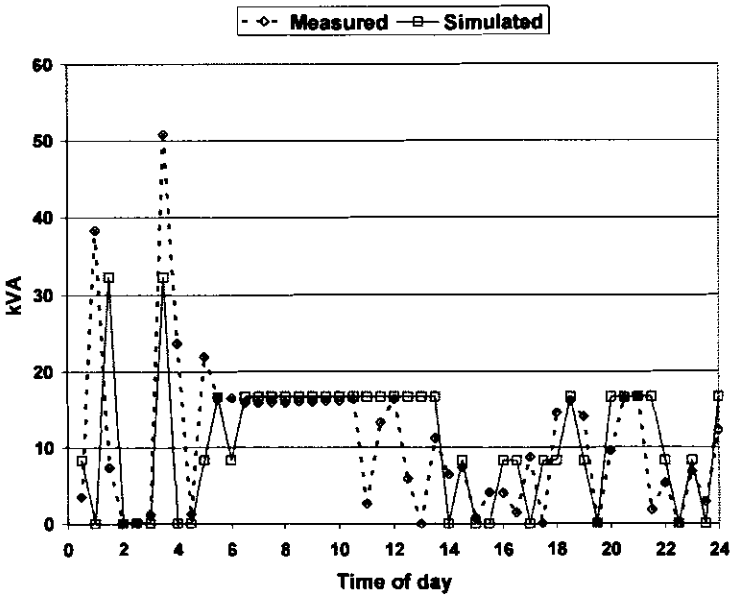


Figure 7: Comparison between simulated and measured data – 12/12/2002

From Figure 5 to Figure 7 it can be seen that electrical demand is predicted with sufficient accuracy in the peak demand periods. In all occasions the demand is however slightly under-predicted during off-peak hours when all the heaters are able to operate. This can be attributed directly to the simulation time step of 7½ minutes, which influences the accuracy of demand prediction when the heaters are on for very short periods. During peak demand periods however, when only the heat pump is allowed to operate if hot water supply is sufficient, the demand is predicted quite accurately. The recorded peak demand is predicted to within 3% of the actual value.

It should be noted that the back-up heaters were not activated during peak demand periods in this case study, since water consumption was not high enough for this to occur.

Maximum demand during peak and off-peak periods

The measured and simulated maximum demand during peak and off-peak periods are shown in Table 3. The error in simulation of maximum demand during peak periods, when the rest of the building's electrical demand is high, is predicted with an error of only 2.4%. When this is viewed as its contribution to the total building demand, which in this specific case study is ±180 kVA, the error reduces to only 0.2%.

Table 3: Measured and simulated maximum demand

	Peak (6:00-22:00)	Off-peak (22:00-06:00)
Measured maximum demand and time of occurrence	17.1 kVA @ 10:30-18/12/02	48.06 kVA @ 0:30-23/11/02
Simulated maximum demand and time of occurrence	16.7 kVA @ 10:30-18/12/02	42.2 kVA @ 0:30 23/11/02
Error	2.4%	13.9%

5.2 Simulation of a conventional in-tank electrical resistance heater system

The second case study is a conventional in-tank heater system installed in a Cape Town hotel. Typical hot water consumption patterns for this hotel was analysed in Chapter 2. The system specifications are provided in Table 4.

Table 4: Systems specifications used in simulation

Storage capacity	10000 litres
Heating capacity	2x45kW electrical resistance heaters
Plant configuration	2 Storage tanks connected in series, each installed with one in-tank electrical resistance heater
Set-point temp, dead band	70°C, 4°C
Thermostat position, set-point	Stage 1: On set-point temp. Stage 2: 60% of height - Set-point 60°C
Water consumption	Period 1/9/2002-30/9/2002
Ambient conditions	Period 1/9/2002-30/9/2002
Load control	Load shed: 16:00 – 18:00

Electrical energy consumption

Comparative figures for electrical energy consumption are shown in Table 5. As in the previous example, the measured and simulated total electrical energy consumption compares well, due to the calibration of this result by variation of the heat loss constant until convergence is obtained to within 0.25%. The heat loss constant obtained in this simulation was 0.81% of heat losses from the total tank energy content, relative to ambient, per hour.

Table 5: Electrical energy consumption

	Electrical energy consumed
Simulation	23220 kWh
Measured	23215.45 kWh
% Error	0.02 %

Comparison of 24-hour demand profiles.

Figure 8 to Figure 10 show demand profiles for three randomly chosen measurement periods, comparing simulation results and measured data. Results obtained are very similar in terms of accuracy to the first example. The heating demand in peak electrical demand periods, which also coincides with peak hot water demand, is predicted with good accuracy. In this example a secondary heating stage is activated by a thermostat situated at $h^*=0.6$. This is predicted with good accuracy, as can be seen from Figure 8 to Figure 10. In the off-peak periods early in the morning, the heating demand is however spread over a longer period by the simulation program when compared to the measured data. The amount of energy consumed in this period is however predicted accurately. This means that the errors made in demand prediction in these off-peak periods are not an energy consumption calculation error, and will therefore have no influence on the calculations for the rest of the day.

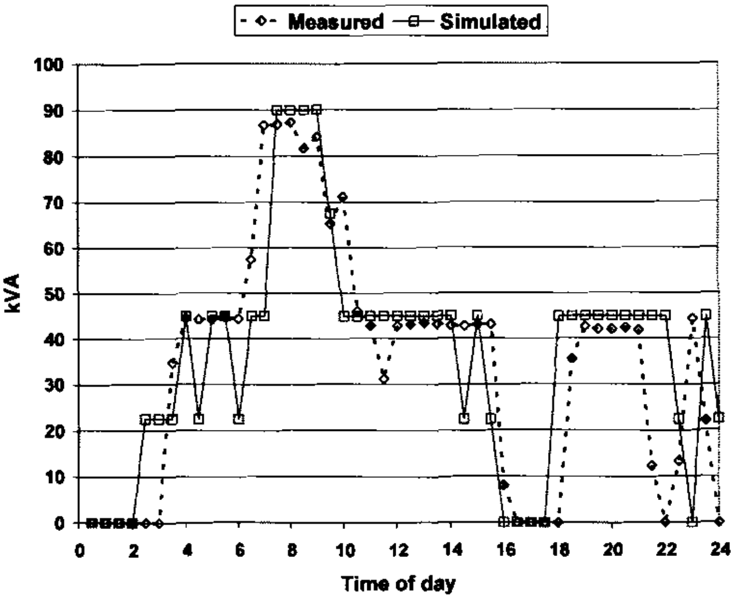


Figure 8: Comparison between simulated and measured data – 13/9/02

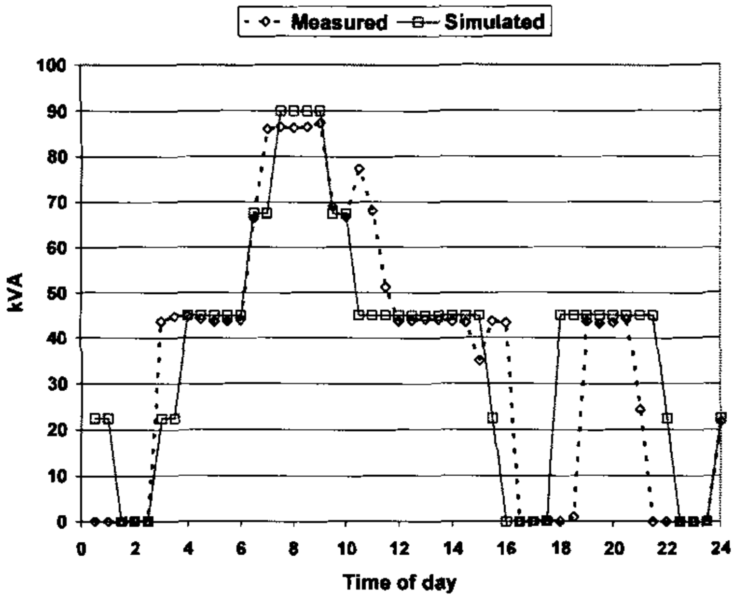


Figure 9: Comparison between simulated and measured data – 14/9/02

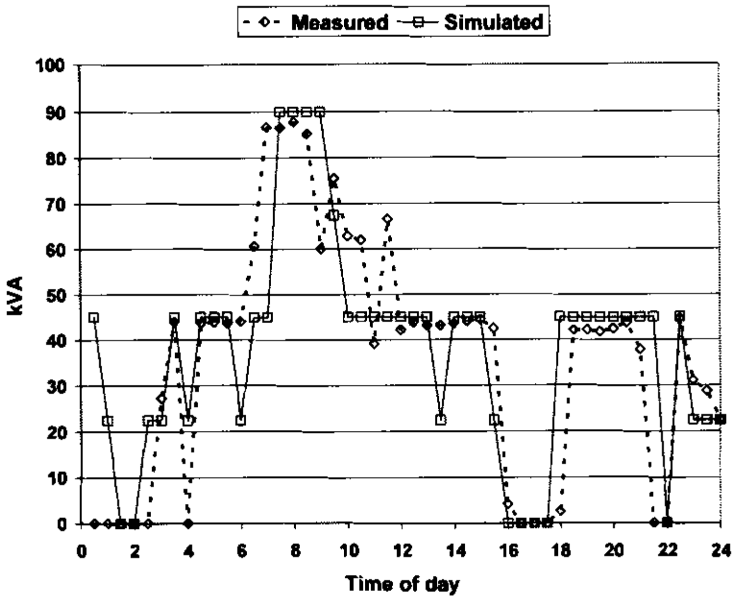


Figure 10: Comparison between simulated and measured data – 22/9/02

Maximum demand

The measured and simulated maximum demand is shown in Table 6.

Table 6: Measured and simulated maximum demand

	Peak
Measured maximum demand and time of occurrence	89.19 kVA @ 9:30- 9/11/02
Simulated maximum demand and time of occurrence	90.00 kVA @ 9:30- 9/11/02

The maximum demand is predicted with an error of 0.9%. When this is viewed as its contribution to the total building demand, which in this specific case study is ±250 kVA, the error reduces to 0.3%.

6 Verification of simulation routine: Prediction of supply temperature

As mentioned in the first section of this paper, hot water availability remains the most important constraint in the design of a hot water system. This section verifies that the simulation routine provides a good prediction of the hot water supply. This is done for both in-tank and in-line configurations.

6.1 Simulation of a conventional in-tank heating system

A conventional in-tank electrical heating system is simulated in this section. The hot water demand at this system is very high, which causes large fluctuations in hot water supply temperature. The system specifications are shown in Table 7.

Table 7: Systems specifications used in simulation

Storage capacity	20000 litres
Heating capacity	176kW (2 x 88kW)
Plant configuration	2 Storage tanks connected in parallel, each installed with an in-tank electrical heater
Set-point temp, dead band	65°C, 4°C
Thermostat position, set-point	65°C, near the bottom of the tank
Off-peak timer	None
Water consumption	Period 14/8/2003 – 19/8/2003
Ambient conditions	Period 14/8/2003 – 19/8/2003

The correlation between measured and simulated energy consumption needs to be determined first to obtain a heat loss factor. A heat loss factor of 0.72% per hour was chosen with the system set-point being 65°C, which is halfway between the 0.64% per hour and 0.81% per hour obtained for 60°C and 70°C set-points respectively. Figure 11 shows the comparison between the simulated and measured 24-hour electrical demand profile for a specific day. A good correlation exists between measured and simulated data, with only a 0.2% difference between simulated and measured energy consumption. The electrical demand profile is also predicted with good accuracy, as shown in Figure 11.

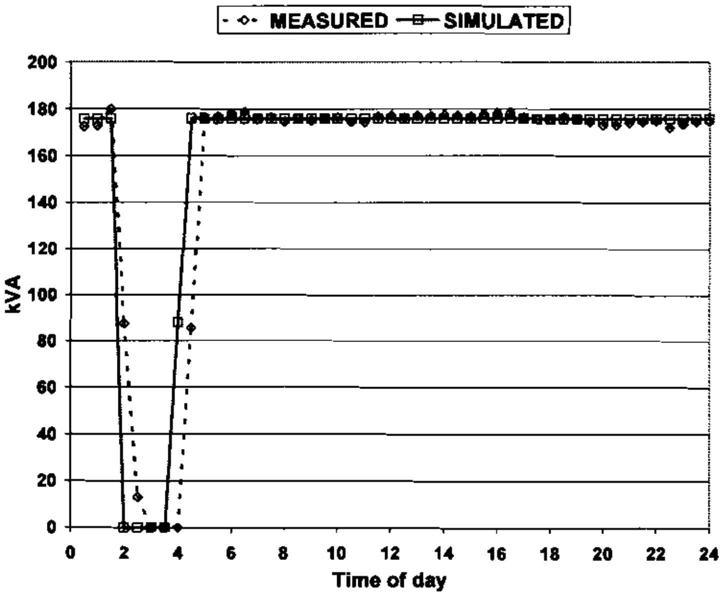


Figure 11: Comparison between simulated and measured electrical demand profile

Figure 12 shows a comparison between simulated and measured hot water supply temperature for the specific day used in Figure 11. The fluctuation trend of the simulated hot water supply temperature compares well with measured data. Small differences occurring during off-peak periods can be seen between simulated and measured data. The minimum temperature and its time of occurrence are however predicted with good accuracy by the simulation model. The measured minimum temperature was 42.2°C occurring at 17:00, and the simulated minimum temperature was 42.5°C also occurring at 17:00.

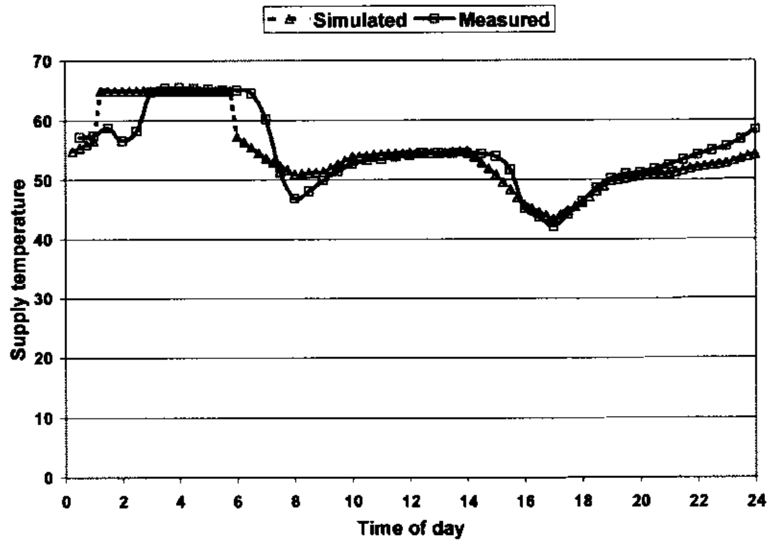


Figure 12: Comparison between simulated and measured hot water supply temperature

6.2 Simulation of an in-line heating system utilizing a DSM controller

In this section data from an electrical resistance in-line heating system, as described in Chapter 4, is used to verify the electrical demand and outlet temperature prediction made by the simulation routine. The system incorporates a DSM controller that sheds the electrical load between 18:00-20:00. A thermostat is placed in the storage tank at a height of $h^*=0.9$ with a set-point of 40°C, which overrides this load shedding signal to prevent hot water run out.

Table 8: Systems specifications used in simulation

Storage capacity	16000 litres
Heating capacity	216kW in-line electrical resistance heater
Plant configuration	Plant connected in the in-line heating configuration
Set-point temp (In-line heater outlet)	46°C
Main control thermostat set-point	45°C
DSM override thermostat set-point	40°C
DSM controller	Shed load between 18:00-20:00, dependant on DSM thermostat status
Water consumption	Period 09/08/2004-08/09/2004
Ambient conditions	Period 09/08/2004-08/09/2004

Figure 13 shows the comparison between the simulated and measured 24-hour electrical demand profile for a specific day. A very good correlation exists between measured and simulated data, with only slight differences found in demand prediction during the early morning hours. A difference of 0.12% was found between simulated and measured energy consumption. The most important outcome of this result is the accurate prediction of the DSM thermostat overriding the DSM load shed signal before the load-shedding period expired at 20:00. This happened due to the stored hot water in the storage tanks being used up before the end of the load shedding period. The 30 minute integrated values indicate the measured overriding signal to occur at a time of 19:34, while the simulation predicted a time of 19:37.30. The difference can be attributed to the simulation time step of 7½ minutes, whereby the control decision can only be taken at the beginning of the following time step.

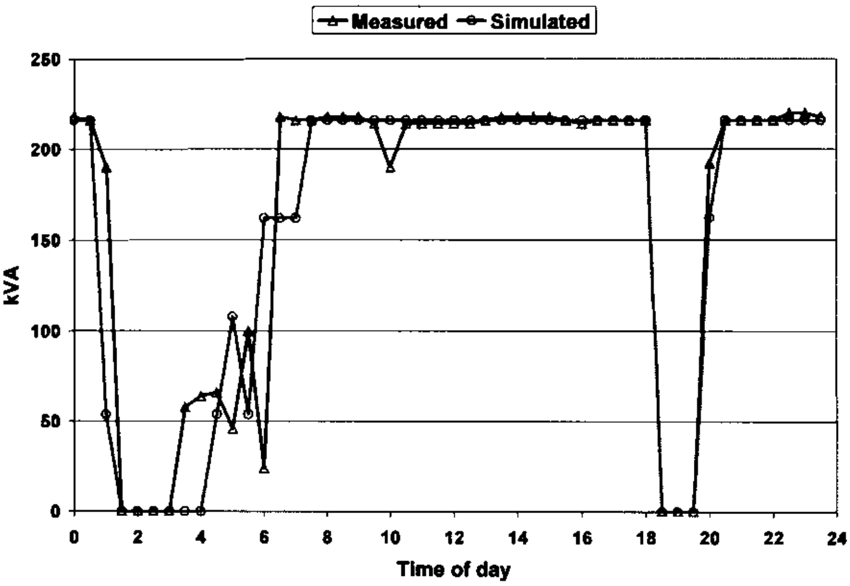


Figure 13: Comparison between simulated and measured electrical demand profile

Figure 14 shows a comparison between the simulated and measured hot water supply temperatures for the specific day used in Figure 13. Hot water supply temperature remains constant through out the day, except for the early morning hours and during the DSM load shed period.

In the early morning hours the temperature increases slightly above set-point. This is due to the small difference between heater set-point (46°C), and main control thermostat set-point (45°C), which controls the heater inlet temperature. This will cause the heater outlet temperature to rise slightly above its normal set-point just before it switches off. This is caused by a minimum temperature rise of 5°C, governed by the temperature control valve.

During the DSM load-shedding period the outlet temperature drops below the set-point value, since the stored thermal energy in the tank is close to being used up. Both the measured and simulated outlet temperature drops to 37°C, which corresponds well with the DSM thermostat set-point of 40°C less a 4°C dead band value.

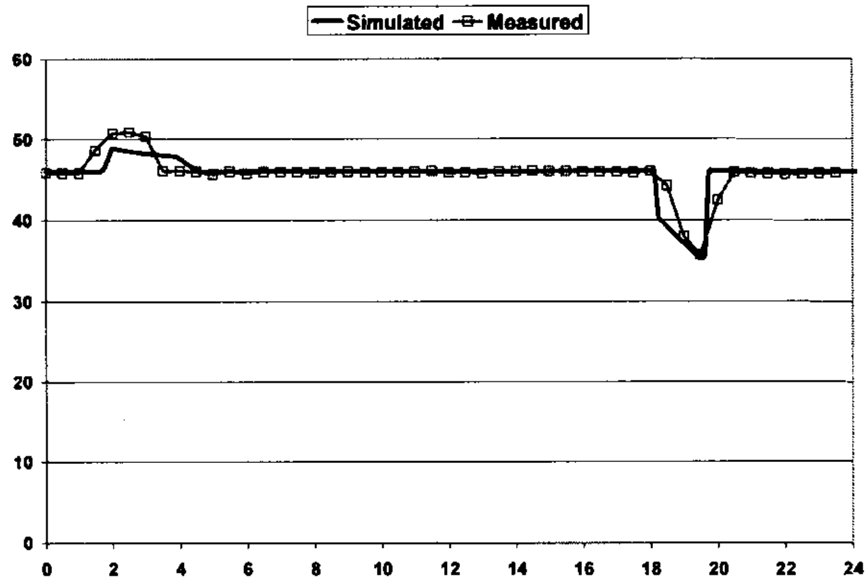


Figure 14: Comparison between simulated and measured hot water supply temperature

7 Discussion of results

Energy consumption and heat loss

In the first example electrical energy as well as thermal energy were compared to the measured data. This was due to the presence of a heat pump, with both electrical and thermal measurements being taken at the installation. In the second example only electrical energy was compared, due to the presence of only direct electrical resistance heaters. In both cases the total *simulated* electrical energy consumption was manipulated to equal the *measured* electrical energy consumption, by means of varying a heat loss constant. Resultant heat loss constants were also shown for both examples.

This provides an interesting view on the validation of the heat loss constant used in the simulation. The storage tanks in the two examples are of different sizes, but of exactly the same construction in terms of physical layout and thermal insulation. This is due to both systems being specified and built by the same contractor. The simulation of the second system provided a heat loss constant which is 26.5% higher than the first system. The set-point temperature of the second system is however 27% higher than the first system relative to the average ambient conditions at each site. This demonstrates the effectiveness of using such a heat loss constant in the simulation, The total amount of hot water consumed and consumption patterns will also have a significant influence on the total standing losses, but this will be reflected in the total system efficiency rather than in the heat loss constant.

The results discussed in this section provide a high level of confidence in the simulated results in terms of energy consumption, but this will be dependent on the accurate specification of a heat loss constant for different systems. It is clear from the results obtained that this heat loss constant will be a function of the temperature set-point, as well as the physical layout and thermal insulation properties of each system. The varying daily and seasonal ambient conditions will not influence this heat loss constant, since the simulation program relates the standing losses to ambient conditions during each time step.

Demand prediction

Results obtained from all four case studies show a high level of confidence in the demand prediction capability of the simulation program in peak periods. Research on water consumption profiles (Lane (1996)) has shown that peak hot water demand usually coincides with peak electrical demand in residential and commercial buildings. It is therefore clear that the less than accurate prediction of heating demand in periods of low electrical and hot water demand is of no concern, provided that it does not influence the demand prediction in peak periods. For a clear understanding on the simulation methodology, the reasons for these demand prediction errors in low demand periods still needs to be explained. The following reasons are stated for it:

1) During periods of low hot water demand, when the storage tanks are filled with hot water, the heaters can be operational for only short periods of time. Measurements show the heaters to be on for periods as short as 3-10 minutes. The simulation time step of 7½ minutes will therefore provide some inaccuracy during these periods.
2) For the accurate simulation of a thermostat dead band, which influences the operation of heaters, an accurate temperature distribution profile in the storage tanks is required. A stratified storage tank model with a large number of nodes is required for this level of accuracy. Even these models will not be able to accurately predict the temperature distribution, due to several de-stratification factors, such as mixing between layers during charge and discharge cycles, vertical conduction in tank walls and heat transfer between layers. It is therefore clear that the exact simulation of a thermostat dead band is very difficult in practice. For large variations in tank temperature, for instance during high hot water demand or constant heating demand, this is not a problem. In periods of low water demand however, the associated small variation in tank temperature is very difficult to simulate.

Hot water supply temperature prediction

Results obtained from the case studies show that the minimum supply temperature and its time of occurrence are predicted with good accuracy. Both mixed tank and stratified tank cases were simulated, and the stratified tank case study was also subjected to load shedding with temperature based intervention. Slight differences between measured and simulated temperatures occurred during periods of low hot water demand in the early morning hours. These errors are however within acceptable limits, and only occur during the off-peak periods when hot water demand is very low and the tanks are filled with hot water, and are therefore of no concern.

8 Summary of results and conclusion

This chapter provides technical background and verification of a model developed for predicting heating demand and hot water availability in sanitary water heating installations. A first law analysis is employed to account for the flow of energy in the water heating system, and a simple three-node temperature distribution model is employed based on the assumption of thermal stratification. This verification study was done using measured data available from projects as discussed in Part one of the study. Several case studies were evaluated for both mixed tank and stratified tank type systems. The results provide a high level of confidence in the demand and energy usage prediction capability of the model. The minimum hot water supply temperature and its time of occurrence were also predicted with good accuracy.

This simulation model can become a valuable design optimization tool for sanitary hot water systems in general. The model will also be used in Chapter 6 and Chapter 7 of this thesis where the in-line water heating system is optimised for commercial and industrial applications. The simulation routine can therefore provide a measure of the technical, and ultimately the competitive economic performance of well designed systems.

CHAPTER 6 - OPTIMIZATION GUIDELINES FOR COMMERCIAL BUILDING SANITARY WATER HEATING SYSTEMS

Abstract

In the previous chapter a simulation program for sanitary water heating systems was developed. Simulation results were verified using data from actual installations as discussed in Chapter 3 and Chapter 4 of the thesis. In Chapter 2 hot water consumption patterns from these installations were analysed and discussed. The hot water consumption patterns that were obtained for hotels are now incorporated into the new simulation program. This chapter now attempts to optimize the operation of the in-line heat pump water heating system in commercial buildings such as hotels. Several optimization phases are completed sequentially, with each phase using the best results from the previous optimization. This method maintains the feasibility of previously optimised parameters used as initial values in each following optimisation phase. All optimizations are evaluated in terms of economic performance, with the main criteria being Internal Rate of Return (IRR), against a baseline system. This baseline system is constructed according to the typical system found in the South African commercial building sector.

Optimization phases include the optimization of heat pump heating capacity, system storage capacity, and secondary heater capacity and control stages. Final control optimizations are also made to maximise the runtime of the heat pump to further improve the overall energy efficiency of the system. All results are expressed non-dimensionally, to allow the use of an optimized guideline for a typical system, but of any size.

Final results clearly show that, if implemented, the optimisation proposals can significantly increase cost effectiveness of sanitary water heating systems in the commercial building sector. Payback periods of less than 2.5 years are expected for the retrofitted systems subject to any of the two types of electrical tariffs found in the commercial sector. An IRR of 47.1% can be obtained for systems operating on a tariff that includes a Maximum Demand (MD) charge, and 47.3% for systems operating on a time-of-use tariff.

The building owner can therefore obtain significant benefits from such an installation. The DSM benefits to the utility are however only realised when the electrical tariff includes a MD charge. Results show that an energy tariff based on a time-of-use energy consumption schedule, which does not include a MD charge, proves to be detrimental to DSM efforts.

1 Introduction

In the previous chapter a simulation program for sanitary water heating systems was developed, based on a simplified first law analysis. Simulation results were verified using data from actual installations as discussed in Chapter 3 and Chapter 4 of the thesis. The results that were obtained provide a high level of confidence in the capability of the simulation model to predict all the important operational parameters of a sanitary water heating system.

This simulation program was created to address the need identified in Chapter 1 to further refine and optimise water-heating methodologies for both commercial and industrial applications. This chapter attempts to optimize the operation of the in-line heat pump water heating system in commercial buildings such as hotels. Hot water consumption profiles obtained in Chapter 2 for hotels are now provided to the simulation routine, and the in-line heat pump water-heating configuration as discussed in Chapter 3 is used as the starting point for further optimisations.

2 Previous water heating system optimization studies

Previous studies were found in the literature that focussed on aspects of design optimisation for water heating systems. Methods of evaluation ranged from experimental setups for testing new heating configurations, to simulation models used for equipment sizing and impact studies. A number of these studies relevant to this optimisation study are shortly discussed here.

Greyvenstein & Rousseau (1997, 1999) performed simulation investigations to determine the optimum combination of reservoir size and heating capacity for a given application. Results were obtained for a minimum non-dimensional temperature of $T^*=0.9$ (Refer to Appendix A for definitions of non-dimensional parameters). The non-dimensional heating capacity for the heat pump connected in the improved in-line heating configuration was found to be $Q^*=1.06$, for a non-dimensional storage capacity of $V^*=0.4$. For the same non-dimensional storage capacity, the non-dimensional heating capacity of a conventional heater was found to be $Q^*=3.0$. A direct economic comparison is made that shows a technical possibility of an 87% reduction in peak demand. A shortcoming of this comparison is that it was only done for a non-dimensional storage capacity of $V^*=0.4$. Surveys determining the typical specifications of commercial building sanitary water-heating systems (Rankin *et al* (2004)) have however indicated that storage capacities are generally sized to hold 55-75% ($0.55 < V^* < 0.75$) of total daily hot water consumption. Only a small number of installations were found with a storage capacity smaller than $V^*=0.55$, and almost none smaller than $V^*=0.4$.

Peak hot water demand periods are less likely to influence hot water availability in larger storage tanks. The scenario of total tank reheating after a peak hot water demand period is therefore typically avoided. This enables the heating load to be spread over a longer period meaning that the non-dimensional heating capacity can be reduced. It is however generally found that the installed heating capacities in conventional heating systems are still higher than the actual requirement. Previous studies (Hendricks (1993), Pate

(1977)) showed that the conventional in-tank heating methodology significantly influences thermal stratification due to mixing effects. This was also illustrated in the simulation study done in Chapter 4. The heaters are therefore still designed large enough to avoid temperature deficiencies caused by mixing and can contribute significantly to peak demand.

Hiller (1996) tried to address the mixing effects of an in-tank heater by installing additional electrical elements inside the storage tank near the top. This enabled a reduction in the required capacity of the heater installed near the bottom. During periods of high hot water demand, both heaters will however be operating, with a great risk of coinciding with the rest of the building peak demand. Previous studies (Lane (1996)) clearly show that hot water peak demand usually coincides with the building peak electrical demand. The use of a back-up heater is therefore only economically viable if it can be configured to operate mainly in off-peak periods.

A few studies investigated the economic viability of additional thermal insulation on a hot water system. Heat losses can contribute significantly towards the total electrical energy consumption of a hot water system, and several authors (ASHRAE (2003), Hendricks (1993), Van Tonder & Holm (2001)) therefore emphasize the use of sufficient thermal insulation. It was however found that an increase in thermal insulation is only economically viable if the initial insulation on a hot water system is very poor. As expected, only marginal heat loss reductions were obtained when additional insulation were fitted to systems that were already properly insulated (Hendricks (1993)). All the systems encountered in the study and discussed in Chapter 3 and Chapter 4 complies with the standards for thermal insulation as provided by ASHRAE. This means that additional thermal insulation will only decrease heat losses marginally, and the added cost involved makes this an option with no economic benefit.

The issues discussed in this section indicate several shortcomings in current design philosophies. The following preliminary issues can be identified, that need to be addressed in this study.

1. Comparisons should be done for a range of storage capacities typically found in practice, rather than only the minimum storage capacity satisfying the temperature requirements, as done by Greyvenstein and Rousseau (1997, 1999).
2. Back-up heating should be configured to operate as little as possible during peak hot water demand periods.

3 Baseline system

Surveys conducted since 1998 show that the heating systems found most commonly in South Africa in commercial buildings such as hotels, hospitals and tertiary education residences, are conventional in-tank heating systems. This type of system consists of one or more storage tanks with in-tank electrical elements installed near the bottom. This information will now be used to create a virtual baseline system against which all optimization procedures for the in-line heat pump system will be compared and evaluated.

A Baseline system is created according to the following basic specifications:

- Layout: Vertical storage tanks with electrical elements immersed in-tank near the bottom. The storage tanks are connected in parallel.
- Non-dimensional storage capacity: $V^*=0.65$ and non-dimensional heating capacity $Q^*=1.95$.

3.1 Input

Water consumption

Water consumption is directly related to the occupancy of the hotel, as shown in Chapter 2. The occupancy in a hotel fluctuates on a day-to-day basis. For the purposes of simulating the occupancy fluctuation for a month, the program creates a basic occupancy cycle as a function of the supplied maximum and average occupancy. The typical daily profile for hot water consumption as obtained in Chapter 2 is also provided to the program.

The following inputs are provided to the program. These inputs will remain fixed for both the baseline system and optimized systems, thereby enabling direct comparison of performance.

- Maximum occupancy: 210 people
- Average occupancy: 140 people
- Maximum amount of hot water consumed per person daily: 109.6 litre at 60°C.
- Minimum inlet water temperature in winter is 12°C. With the outlet controlled at 60°C, maximum $\Delta T=48°C$.

Tariffs

Two different tariff structures are currently found in the South African commercial building sector. Both tariff structures are now used to determine the operational cost of a system.

Tariff 1: Maximum Demand with consumption flat rate

This tariff structure consists of two parts:

- Maximum Demand is charged for the maximum 30-minute integrated electrical demand of the water heating system, for each month. The hot water system demand will only contribute to the building peak demand during periods of high overall demand. Since building demand is not available, an assumption will be made that the building peak demand can occur anytime between 7:00-22:00. The maximum demand of the water heating system will therefore be recorded between 7:00-22:00 by the simulation.
- Energy consumption is charged at a flat rate regardless of the time of use.

Tariff 2: Two-part time-of-use consumption rate

This tariff structure does not include a Maximum Demand charge. Energy consumption is charged at two different rates during the day, reflecting peak and off-peak periods.

Rates charged

Table 1 shows the typical tariff charges that will be used in calculating all the results obtained in this chapter. These tariff charges reflect the average proposed tariff charges from ESKOM in 2004.

Table 1: Typical tariffs used in the South African commercial building sector

	Tariff 1	**Tariff 2**
Maximum demand	R54.00 / kVA	-
KWh consumption	R0.12 / kWh	22:00 – 7:00: R0.16 / kWh 7:00 – 22:00: R0.39 / kWh

System heat loss characteristics

Typical lumped factors for standing losses from the storage tank have been determined in Chapter 5. Standing loss fractions will be taken as 0.65% of the stored energy lost per hour. Ringmain losses will be taken as a typical ringmain return flow rate of 0.1 l/s, resulting in an average temperature drop of 10°C between ringmain supply and return. This complies with accepted standards (BS-1394: Part 2 (2001)) for ringmain circulation pump installations. The simulation program relates both standing losses and ringmain losses to the ambient and stored water temperatures as described in Chapter 5.

Simulation period

A 12-month simulation is done using the specifications and input data provided above. The simulation routine takes into account the effect of seasonal changes on ambient conditions, inlet water temperature, and the seasonal change in hot water consumption as described in Chapter 2.

3.2 Baseline system specification

With the specifications provided, a baseline system with the following specifications is created.

- Storage capacity: Using V^*=0.65 results in a storage capacity of 14000 litters.
- Heating capacity: Using Q^*=1.95 results in a heating capacity of 93.1 kW, leading to the selection of a nominal heating capacity of 96kW.

The typical installation cost of this specific system is determined as R 55 300.00.

3.3 Results

Figure 1 shows the simulated results for a typical 24-hour operation period for the system. Electrical energy consumption by the heaters, and thermal energy produced by the heaters are shown for the 24-hour period. Since an electrical resistance heater is used, the electrical energy consumed and thermal energy produced by the heaters is identical. The water consumption profile of the building is also shown on the graph, presented in terms of thermal energy consumption ('thermal building' on the graph). It can be seen that the water heating system contributes its full installed heating capacity to the building demand during the middle of the day when hot water demand is high, leading to high running costs based on Tariff 1. The heaters are also operating mainly during the daytime, leading to high running costs based on Tariff 2 as well. Table 2 provides a summary of operational costs for the baseline system. Operational cost is expressed as cents (ZAR) per kWh of thermal energy consumed.

Table 2: Simulated annual average operating cost for baseline system

	Tariff 1	Tariff 2
Operating costs	36.92 c/kWh (ZAR)	36.22 c/kWh (ZAR)

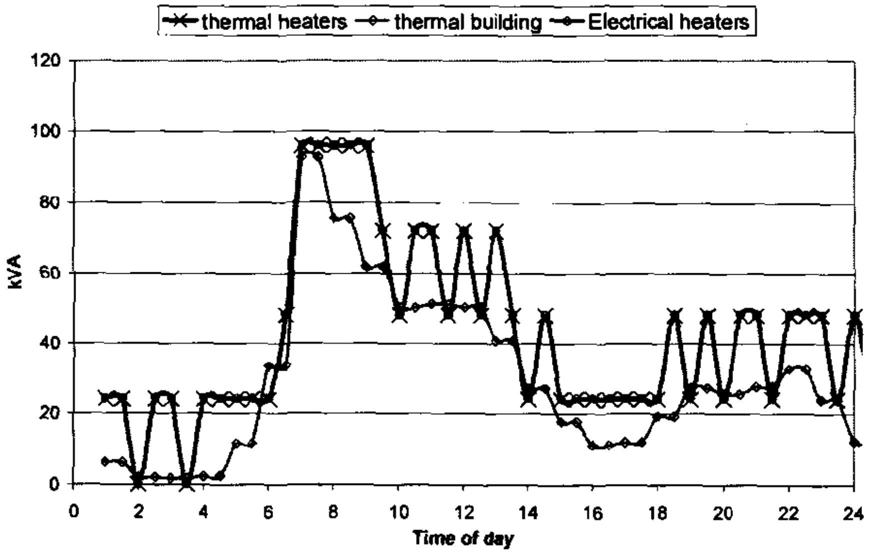


Figure 1: Typical 24-hour electrical demand profile for the baseline system

4 Optimization approach

Several optimisation phases will be completed, with each phase addressing a major component of the in-line heat pump system. Optimisation phases include optimising heating capacity of the heat pump, heating capacity and control of the back-up heater, and final control optimisations to maximise the runtime of the heat pump. The optimisations will be performed sequentially, with each optimisation using the optimised result of the previous phase. This approach maintains the feasibility of previously optimised parameters used as initial values in each following optimisation phase (Martinsen *et al* (2004)). The drawback of this approach is however the fact that it provides a local optimum instead of a global optimum, i.e. an optimum only for in-line heat pump systems applied in commercial buildings with the stated input values. It is however the aim of the chapter to provide an optimised system for buildings on a commercial energy tariff only, which justifies the use of the sequential optimisation approach.

5 Phase 1: Optimization of heat pump and storage capacity

In Phase 1 the conventional in-tank heating system is replaced with an in-line heat pump system. In this section the capacity of the heat pump acting as primary heater is optimized, as well as the storage capacity of the system. The two variables are evaluated together during the routine. The reason for this is that the optimal heating capacity will vary for different storage capacities. The optimal heat pump size can then be chosen for a system with a fixed storage capacity, or the optimum result for both heating and storage capacity can be specified for a new plant. An electrical resistance in-line heater used for back-up heating is also connected in the improved in-line heating configuration. The purpose of the back-up heater is to boost heating during off-peak periods, and provide assistance when additional heating is required in peak periods.

The back-up heater is initially sized to heat the maximum amount of hot water consumed per day in 20 hours. This is a non-dimensional heating capacity of $Q^*=1.2$, which results in a required heating capacity of 57.8 kW. The closest available heating capacity for a three-phase system in practice will be 60 kW. The control algorithm will activate the back-up heater to assist with heating when 40% of the maximum tank energy content remains. This is required to prevent hot water deficiencies during the times when only the heat pump is scheduled to operate. A timer will also allow the back-up heater to boost heating during the early morning hours between 00:00 – 05:00 for Tariff 1, since the building demand is low during these periods. In the case of Tariff 2 the heaters will be allowed to operate between 00:00 – 07:00.

An important design condition is the minimum required outlet temperature. A non-dimensional temperature of $T^*=0.8$ is provided as the minimum required outlet temperature. This implies that although a certain system configuration might be economically viable in terms of operational cost, it will not be used if the minimum required outlet temperature cannot be maintained at all times.

5.1 Additional installation cost compared to baseline system

Valuable experience was gained from research projects as described in Chapter 3 regarding the typical cost involved with commercial water heating installations and retrofits. The improved operation is obtained by adding heating equipment, improving heater configuration and control, and variation of storage capacity. The costs involved will therefore be reflected by the following:

1. Cost of heating equipment, including heat pump and electrical in-line heater with circulation pumps.
2. Cost of storage tank.

3. Plumbing and electrical costs to install heating and control equipment in the correct configuration.
4. Fixed costs per plant, including transport and rigging.

The added cost involved in the phase 1 installation is as follows:

1. Fixed cost: Back-up electrical in-line heater including plumbing fitment and electrical connection, control equipment, transport and rigging. This results in a fixed cost of R 44-600.
2. Heat pump including plumbing fitment and electrical connection. This cost will be determined by the following linear equation, with Q_n the nominal heat pump capacity. Nominal heat pump capacity is the thermal energy (kW) produced by the heat pump at 10°C Wet-bulb ambient temperature and 60°C outlet water temperature.

$$C_h = 1519.2 \cdot Q_n + 40008 \qquad \textbf{Eq 1}$$

3. Storage tank: Cost will be determined by the following equation, with V_s the capacity in litres.

$$C_s = 2.5986 \cdot V_s + 7487.7 \qquad \textbf{Eq 2}$$

Since system performance will be compared to the baseline system performance, the cost difference between the base system and the phase 1 system will be considered as the added cost of installation.

5.2 Results

All the results presented in this section are expressed in non-dimensional terms. Results are presented by plotting the internal rate of return (IRR) vs. non-dimensional storage capacity, for different non-dimensional heating capacities of the heat pump. The IRR is based on a 10-year life cycle.

Results for Tariff 1

Figure 2 shows the resultant IRR for simulations with different heat pump capacities and storage tank capacities for the system subject to Tariff 1.

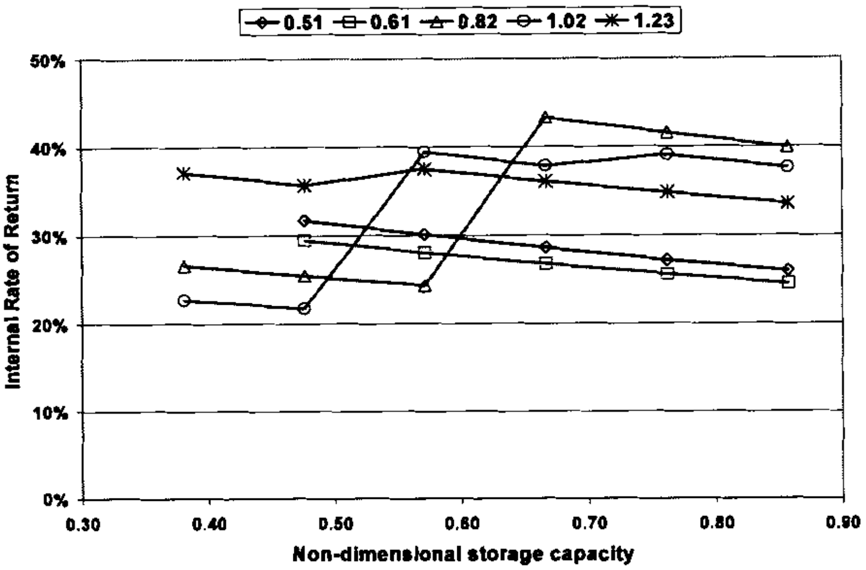


Figure 2: IRR vs. V^* for different Q^* for Tariff 1

The simulation results show that for Tariff 1 systems it is very important to size the heat pump correctly. When the non-dimensional heat pump capacity becomes too high, the capital cost of the system does not justify the savings achieved. When the non-dimensional heat pump capacity is too low, the heat pump cannot produce all the heating that is required during periods of high hot water demand. These peak hot water demand periods coincide with the peak electrical demand period, and the back-up heaters are therefore activated in peak electrical demand periods. This results in a significant loss in savings potential due to an increased peak demand contribution. The back-up heater needs to be activated only once in a month during peak demand periods for it to be recorded as maximum demand for the whole month.

The size of the storage capacity also plays an important role. The higher initial cost and higher fraction of standing heat losses from an oversized storage capacity results in a lower IRR. The morning peak hot water consumption period will however consume a higher fraction of the energy content of a smaller storage tank relative to a larger tank. This leads to the back-up heater being activated during the peak hot water demand period, which results in a high electrical demand contribution. The penalty involved in having insufficient storage capacity is greater than the penalty of having excess storage capacity.

From Figure 2 it can be seen that a non-linear relationship exists between IRR and some of the non-dimensional parameters evaluated. This is due to the diverse combinations of heat pump and storage capacity, which all impacts differently on operational costs of the system. The exception to this is for small heat pump capacities (Q^*=0.51 and Q^*=0.61), where the IRR decreases linearly for increased storage capacity. The reason for this is the increased MD contribution for systems with smaller heat pump capacities as discussed earlier in this section, regardless of storage capacity size. For a heat pump capacity of Q^*=0.82 however the IRR at first decreases from the smallest storage capacity towards a slightly higher storage capacity. From $V^*=0.57$ to $V^*=0.67$ the IRR then increases abruptly. The same discontinuity occurs for $Q^*=1.02$ where the IRR increases significantly from $V^*=0.48$ to $V^*=0.57$. In both cases the increase in storage capacity size reached a level where sufficient thermal energy is stored by the heaters to last throughout the peak hot water demand period. For this reason the back-up heaters are not activated in summer and spring months during peak electrical demand periods. Significant cost savings are achieved in this way due to a decrease in MD contribution, which increases the IRR significantly.

Figure 2 provides the best trade-off between insufficient and excess storage capacity for each heating capacity. It also provides the best options when any existing system with a fixed storage capacity is retrofitted with an in-line heat pump heater. Since the storage capacity cannot be changed in such a system, the graph provides an optimal heat pump size for a specific storage capacity. If a new system is specified, the best combination of heat pump and storage capacity would be $Q^*=0.82$ and $V^*=0.67$. This specification will be used during further optimisations done in this study for Tariff 1 applications. Based on these non-dimensional parameters, the case study plant will use a 40kW heat pump unit and a 15000-litre storage tank.

Results for Tariff 2

Figure 3 shows the resultant IRR for simulations with different heat pump capacity and storage tank capacity for systems subject to Tariff 2. IRR decreases with an increase in both heat pump capacity and storage capacity. Smaller heat pump sizes and storage capacities will lead to the activation of the back-up heater during peak demand periods. This will however only occur during days when the occupancy of the hotel is high, and will only happen for short periods of typically less than two hours per day. Since no maximum demand is charged for, the heaters can be activated for these short times during peak hours with only a relatively small penalty in energy consumption cost. Most importantly however, this loss is limited to only a specific day, instead of influencing the whole month, as is the case when maximum demand is charged. This explains the increasing IRR with decreasing non-dimensional heating capacity and storage capacity shown in Figure 3.

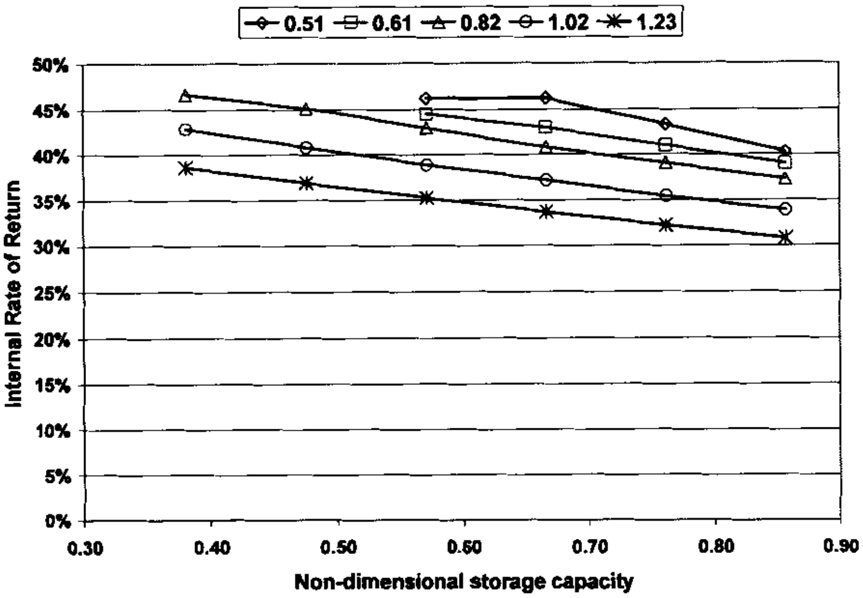


Figure 3: IRR vs. V^* for different Q^* for Tariff 2

It is however important to note that the non-dimensional heating capacity and storage capacity cannot become too small. Simulations for $Q^*<0.51$ resulted in the non-dimensional temperature dropping below the minimum required level of $T^*=0.8$, even with an adequately sized storage tank. For $Q^*=0.51$ the IRR also started to drop off for $V^*<0.67$ due to a very high fraction of back-up heating required to avoid hot water deficiencies. When a storage capacity smaller than $V^*=0.57$ is used, the minimum allowed heating capacity is $Q^*=0.82$.

The best combination of heat pump and storage capacity for Tariff 2 would be $Q^*=0.51$ and $V^*=0.67$. This specification will be used during further optimisations done in this study for Tariff 2 applications. Based on these non-dimensional parameters, the case study plant will use a 25kW heat pump unit and a 15000-litre storage tank.

6 Phase 2: Optimization of the back-up electrical heater

The purpose of the back-up electrical heater in the in-line heating methodology is as follows:

- To boost heating during periods of low electrical demand for the rest of the building, such as the early morning hours. This is also the time that electricity consumption charges are low in Tariff 2.
- Replacing the heat pump when it is unable to operate, primarily during times when very low ambient temperatures will cause the heat pump evaporator to freeze up. A 'low-ambient' thermostat will prevent the heat pump from operating during these conditions, and the back-up heater will replace the heat pump.

- It assists the heat pump with heating when the energy content of the tank drops below a level where hot water supply can be compromised.

If the primary heating capacity and storage capacity is sized according to the results from the previous section, the heat pump should in most cases be able to provide all the heating during peak demand periods. The back-up heater will only assist with heating during scheduled off-peak periods.

The exception to this is however during winter days, especially when the hotel is fully occupied. During high occupancy days in winter, hot water demand exceeds the heating recovery capacity of the heat pump to such an extent that most of the stored hot water is consumed. This results in the back-up heater being activated during peak demand periods. During most winter days the heat pump will also be unable to operate in the early morning hours. This can extend well into the late morning on very cold winter days. This means that the back-up heater replaces the heat pump in periods that can extend into the building's peak demand period. Figure 4 shows a typical winter day during maximum hot water demand for the building, when the hotel is fully occupied. The Tariff 1 optimised heat pump and storage tank capacities are used for this example.

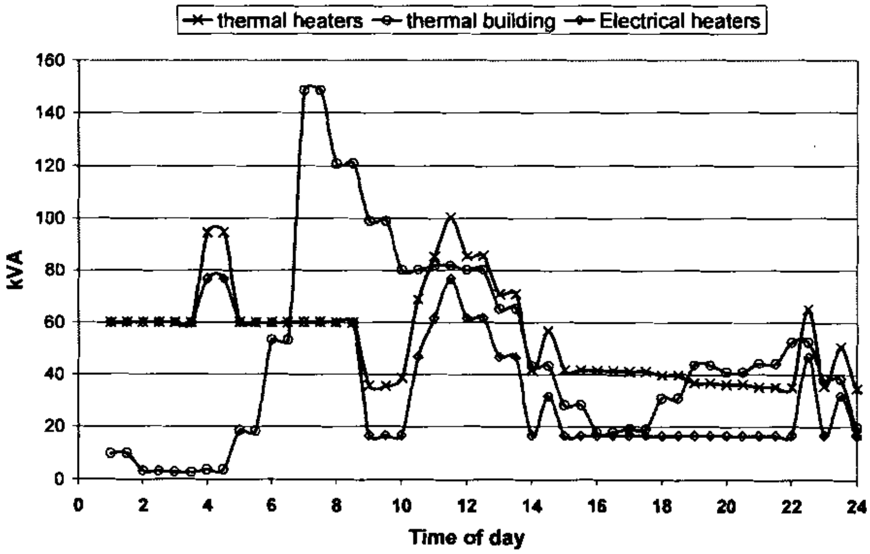


Figure 4: Maximum hot water consumption day in winter for the Tariff 1 system

The heat pump only starts operating at 8:30 in the morning, leading to a peak electrical demand contribution of 60kVA for the hot water system before 8:30. An even higher peak demand contribution of 77kVA is made later in the morning at 11:30. This happened due to the high hot water demand that consumed most of the energy in the storage tanks, and the back-up heater is now called upon to assist the heat pump. This control method effectively avoids hot water deficiencies from occurring. However, as illustrated here the penalty involved in this control philosophy is a significant contribution to building peak demand.

Figure 5 shows the average storage tank temperature for the same day as shown in Figure 4. The temperature bandwidth that would indicate that the storage tank is 'fully loaded' with hot water is also shown. It can be seen that the average temperature in the tank during the 24-hour period is always significantly lower than the 'fully loaded' bandwidth. This implies that the storage tanks are never completely heated up, not even during the off-peak boosting period when the back-up heater assists the heat pump. The ideal scenario to have before the morning peak hot water demand period is to have the average stored water temperature as close as possible to the set-point. This is not achieved in this specific example, and is at least partially responsible for the activation of the back-up heater during peak electrical demand periods.

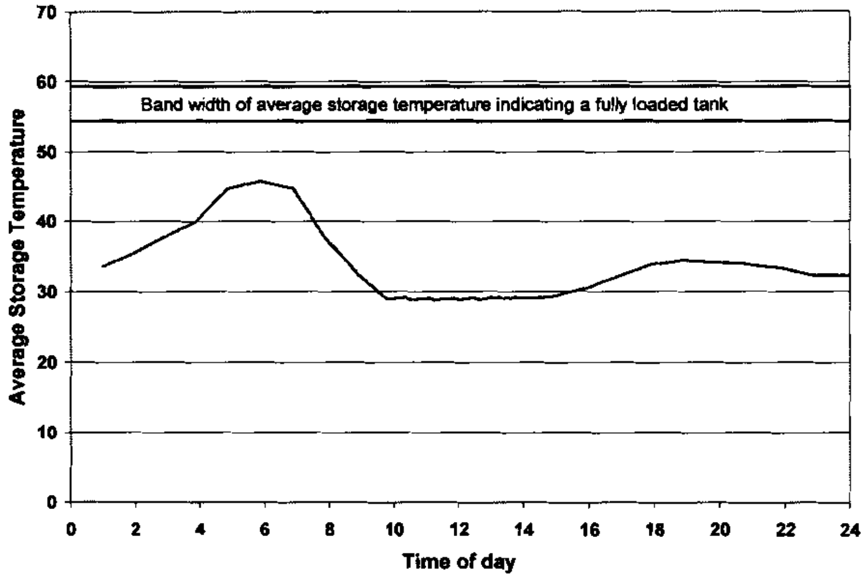


Figure 5: Average tank temperature for case study day

This scenario can be addressed by increasing the capacity of the back-up heater, to enable the tank to be fully heated up before the morning hot water demand peak. The back-up heater can however still be called upon to replace the heat pump during low-ambient conditions, which can extend well into the morning, as shown in Figure 6. In this specific example an 84kW in-line heater is used instead of the 60kW in-line heater as used before. The full installed capacity of the back-up heater still contributes to peak demand.

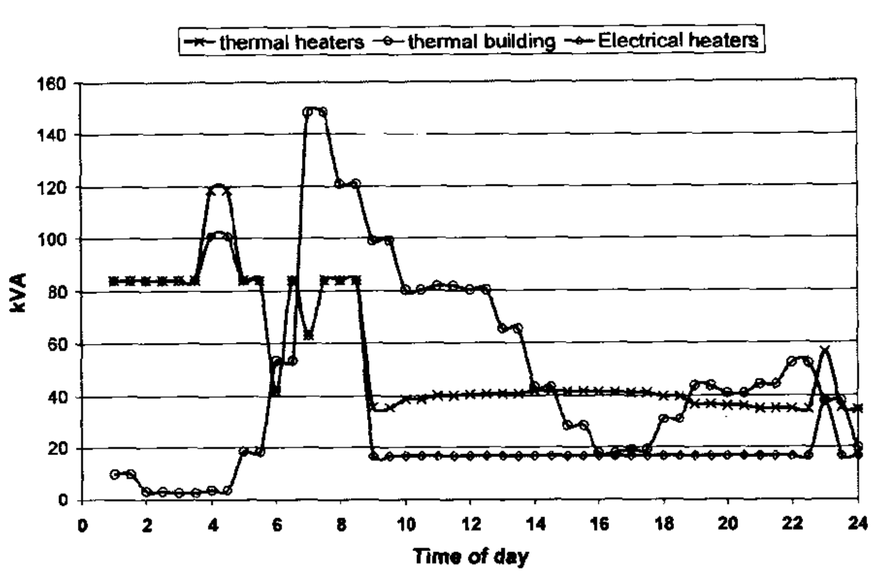


Figure 6: Maximum hot water consumption day with the back-up heating capacity increased – Tariff 1 system

A solution to this problem is to control the back-up heater in multiple stages. The total heating capacity of the back-up heater can be configured to assist the heat pump during the early morning period. This will allow the storage tanks to be fully heated up before the morning peak hot water demand period, without contributing to building peak electrical demand. During building peak demand periods however the back-up heater can be controlled in stages, which will reduce the electrical demand contribution of the hot water system. Only one stage at a time can be called upon to either replace the heat pump during low-ambient conditions, or to assist with heat recovery during peak hot water demand periods when such a situation arises.

A simple control algorithm dividing the back-up heater into three stages is suggested. All three back-up heating stages are activated during the scheduled early morning off-peak heating period. The first stage will be called upon to replace the heat pump during low-ambient conditions. Due to its replacement duties, this heating stage needs to be sized to provide more or less the same heating capacity as the heat pump. The second stage will be called upon to assist the heat pump if the energy content of the tank becomes too low. This stage is sized to avoid a large electrical demand contribution but will still be able to effectively assist with heat recovery without any hot water deficiencies occurring. The third stage only operates during the scheduled off-peak heating period, and its heating capacity is made up of the remaining heater elements available in the back-up electrical heater.

6.1 Added cost

The added cost of this improved control philosophy is:

- The cost involved in the installation of a higher capacity in-line electrical heater,

- The installation cost of an electrical control panel consisting of separate contactors and control relays for each heating stage.

The additional cost involved in this option is R8500 higher than the phase 1 cost.

6.2 Results

Figure 7 shows the resultant kVA demand profile for the same day shown in Figure 4 and Figure 6. The total heating capacity of the back-up heater is increased from 60kW to 84kW ($Q^*=1.75$), and this is divided into three heating stages. The first heating stage is 36kW ($Q^*=0.75$), and second and third heating stages are both 24kW ($Q^*=0.5$). The demand contribution of the hot water system during the peak electrical demand period is reduced from 77 kVA to 41 kVA. Minimum outlet temperature remains above $T^*=0.8$ throughout the day.

Table 3 provides a comparison in terms of IRR, between installations with and without the multiple stage back-up heater control. Comparisons have been done for both Tariff 1 and Tariff 2 optimized installations as obtained in Phase-1 simulations.

Results show that the IRR is improved for Tariff 1 type systems, due to the decrease in peak electrical demand contribution in the winter months. The added cost of the improved back-up heater control can therefore be justified. In Tariff 2 type systems, the IRR is decreased, since the benefit of reduced peak demand contribution is not reflected in the tariff charges. The improved back-up heater control therefore does not increase savings, and the added cost can therefore not be justified. From these results it is clear that improved control mechanisms that results in a reduced peak demand contribution can only be justified if the electrical tariff includes a maximum demand charge.

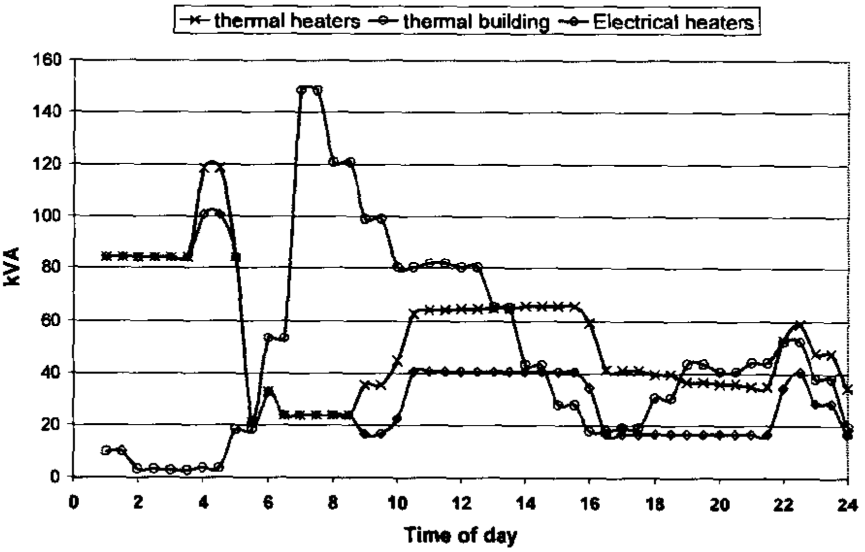


Figure 7: Maximum hot water consumption day with multiple stage back-up heater control – Tariff 1 system

Table 3: IRR for system with or without improved back-up heater control

	Tariff 1 (IRR)	Tariff 2 (IRR)
Without improved back-up heater control	43.3%	46.9%
With improved back-up heater control	45.7%	45.8%

7 Phase 3: Maximizing heat pump runtime

The overall coefficient of performance of the water heating system can be improved if the operation of electrical heaters can be minimized. The ideal scenario in terms of energy efficiency is if the heat pump can produce all of the required heat recovery work, with the system COP then approaching the COP of the heat pump. Day-by-day analysis of a full year simulation actually suggests that during most days, especially during spring and summer times, the heat pump can produce all of the required hot water. During these days no additional heating is required from the back-up electrical resistance heaters. Current control philosophy however does not allow this, since the back-up heater is activated during the scheduled early morning off-peak period as discussed in previous sections. The back-up heater is therefore activated each day during the off-peak period, regardless of whether it is actually required or not. Simulation results from previous sections show this type of control to be of crucial importance during days of high occupancy, to avoid hot water deficiencies or the activation of this back-up heater during peak electrical demand periods.

To determine the potential for additional energy savings, the number of days that the back-up heater is actually required in a typical year during off-peak periods needs to be determined. This is achieved by reconfiguring the control algorithm of the system to allow no back-up heater operation during off-peak periods. The heater will now be activated by thermostat control rather than timer control, only when it is really required later in the day during peak demand periods. This method is also double checked by determining the number of days that the heat pump, producing all the required heating during off-peak periods, actually switches off before the end of the off-peak period. This should indicate that the storage facility is heated up completely by the heat pump without the assistance of the back-up heater. Simulation results for thermal energy consumed by the building and thermal energy produced by the heaters for a 30-day period is shown in Figure 8. The 30-day graph shows that the back-up heaters were activated during 8 days in the simulated month. This happened only during the days when occupancy and therefore hot water consumption was very high.

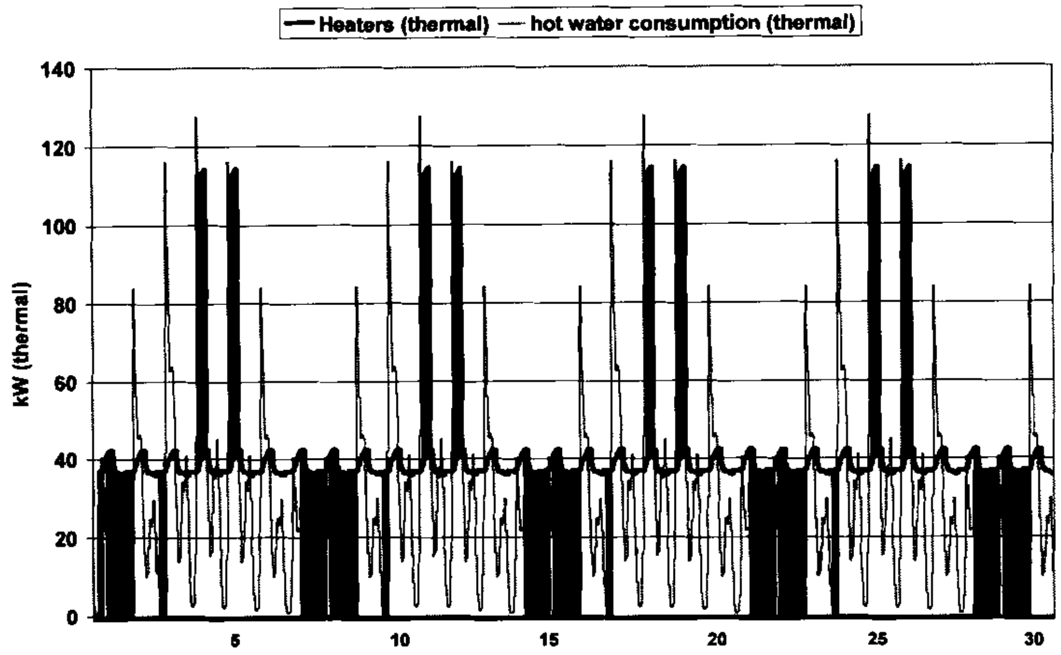


Figure 8: 30-day simulation showing thermal energy consumed by the building and produced by the heaters

The occupancy cycle used in the simulation is representative of real occupancy cycles as obtained in Chapter 2. This occupancy cycle is now used in a full year simulation. The results show that the back-up heaters are activated during 86 days per year in the Tariff 1 type system used in the Phase-2 optimisation, but with the reconfigured control. This implies that the potential for additional energy savings exist for 279 days or 76% of this specific year simulation. The need therefore exists to refine the control algorithm to allow this type of saving.

A look at the average tank temperature during the days when the back-up heater was not required shows that the storage tanks are at least 70% filled with hot water when the scheduled off-peak heating period starts at 0:00. The detailed simulation results shown in Chapter 4 illustrated that thermal stratification exists in the storage tanks for the in-line heating configuration. For this reason a thermostat can be placed at more or less $h^*=0.3$ in the storage tanks to determine whether it is at least 70% filled with hot water. If the tanks are filled to this level with hot water when the off-peak period starts, the back-up heaters will not be allowed to operate, and the heat pump will produce all the heat recovery work in the off-peak period. If the tank is not filled to the required level with hot water, the back-up heaters should be activated. This control intervention can happen anytime during the off-peak period should a severe change in hot water consumption patterns occur.

Additional control will however be required to allow back-up heaters to boost heating beyond the control level at $h^*=0.3$ when required. Without additional control, the back-up heaters will switch off again once the tanks are filled with hot water from the top reaching $h^*=0.3$. This is not an ideal situation, since the storage tank needs to be filled completely with hot water down to $h^*=0.0$, and not only to $h^*=0.3$. An approach is proposed where the thermostat situated at $h^*=0.3$ activates the back-up heaters when needed, but switching-off is done by a thermostat situated at $h^*=0.0$.

Figure 9 shows a typical day when the back-up heater was not actually required to operate, but activated by the standard timed control (Tariff 1 system). Figure 10 shows the same day when the heat pump produced all the heating work, with the improved control preventing the back-up heater from operating during the off-peak period. No loss in hot water availability occurs, and energy savings are increased. The system COP for this specific year simulation was improved from 2.17 to 2.45. This resulted in an additional energy saving of 22000 kWh per year, or an increase in cost savings of R2650 per year. The increase in cost of the control panel to accommodate this additional control measure and the additional thermostat is determined as approximately R1200. The resulting IRR is shown in Table 4.

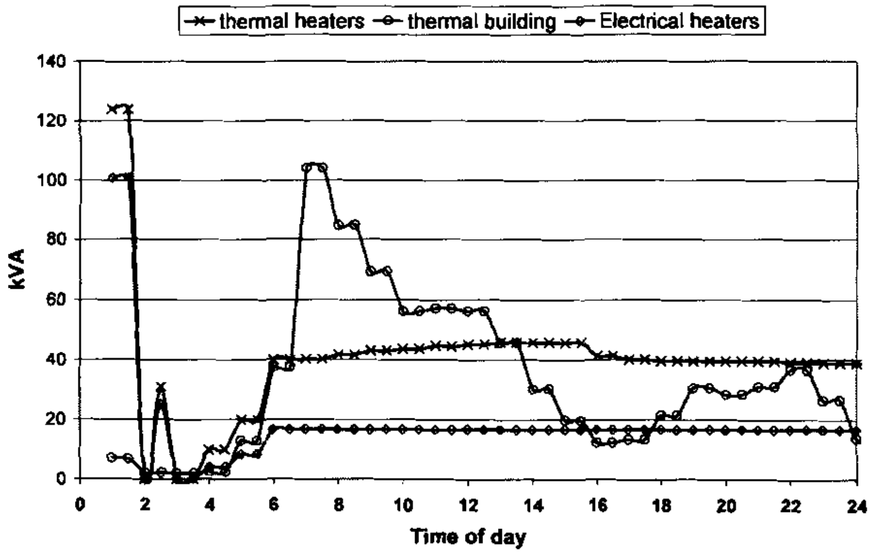


Figure 9: Back-up heating activated by control system

Table 4: Resultant IRR by maximising heat pump runtime

	Tariff 1 (IRR)	Tariff 2 (IRR)
Allowing back-up heater to operate every off-peak period	45.7%	46.9%
Preventing back-up heater to operate when not required	47.1%	47.7%

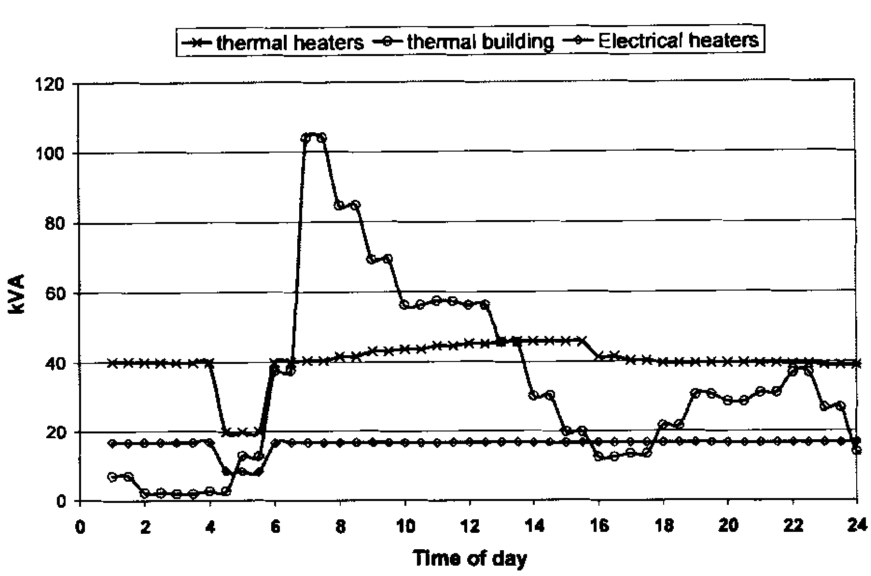


Figure 10: Back-up heating prevented by control system

Table 4 shows that additional savings can be achieved, which justifies the added cost of the new control measures. The increase in IRR is most noticeable in the Tariff 1 application, with a smaller increase in IRR for the Tariff 2 application. At first it seems different to what is expected, since Tariff 2 energy consumption charges are higher than Tariff 1 charges, even for off-peak energy consumption. Since this is an energy savings improvement only, it is expected of the Tariff 2 application to return even higher savings. A closer look at the results show however that since the Tariff 2 system utilises a smaller heat pump (25kW – Q^*=0.51), the back-up heaters are required to assist during off-peak periods for 220 days or 60% of the year. This is compared to Tariff 1 system utilizing a 40kW heat pump, where the back-up heater assists during only 86 days or 24% of the year. The 40kW heat pump system achieves a 22000 kWh yearly reduction in electrical energy consumption as mentioned, with the 25kW heat pump system achieving only a 9500 kWh yearly reduction in electrical energy consumption.

As in the previous section, the use of refined control algorithms is more viable in Tariff 1 type applications. In this case the lack of a demand charge in Tariff 2 is again the indirect cause, since the heat pump heating capacity can be minimized to reduce overhead costs without the heavy MD penalty when the back-up heater is activated in peak periods. With the smaller heat pump heating capacity, the back-up electrical resistance heaters are required to produce a larger fraction of the heating, especially during the low-cost off-peak period. An increase in IRR is however still achieved in the Tariff 2 application, meaning that this improvement in control can still be used effectively to increase energy- and cost efficiency.

The only problem in practice with this additional control measure is the placement of the additional control thermostats. Some existing storage tanks might not have additional sockets at the required level to allow placement of an additional control thermostat. This type of control can therefore only be implemented if the storage tanks allow thermostats to be installed at the required levels, or when a new system is designed where thermostat placement can be specified on the storage tank design.

8 Final testing and evaluation of design guidelines

Before the design guidelines developed in the previous sections can be finalised, it needs to be tested by statistical perturbation of input data. These inputs have previously not been varied since a direct comparison between different configurations was required. The proposed systems will now be tested with the water consumption and ambient data varied between set standard deviations. This approach enables the identification of possible areas of marginal design, where the system operated with in design constraints with the unvaried input data, but outside of design constraints when input data is varied.

A standard deviation for water consumption of 17%, as obtained in Chapter 2, will be used. A standard deviation of 22% for ambient conditions is used (Wentzel (1984)).

25-year simulations based on a Monte Carlo analysis (Labeau & Zio (2002)) are performed for both Tariff 1 and Tariff 2 optimized systems. Parameters being tested during these simulations include the following:

- Does the system still provide the minimum required outlet water temperature of $T^*=0.8$?
- Is the peak demand reductions still realized in Tariff 1 systems?
- Is the overall system COP still achieved?

8.1 Tariff 1 system: 40kW heat pump with three-stage 84kW backup heater

The Monte Carlo Analysis was performed for the Tariff 1 system specified after all the optimisation phases. It was found that the capacity of the back-up heater stage that provides heat recovery assistance during peak electrical demand periods (Stage 2: 24 kW) proved to be insufficient during some of the simulations. The problem might also be caused by the heater being activated too late. This resulted in the supply temperature dropping slightly below the prescribed minimum temperature of $T^*=0.8$ during a few peak hot water consumption days in winter. Two possible solutions are suggested for this problem.

1) Increasing the size of this heating stage from $Q^*=0.5$ (24kW) to $Q^*=0.75$ (36kW) solved the problem, effectively eliminating the hot water temperature dropping below $T^*=0.8$. This results in an increase in peak demand contribution during the three winter months, which causes a decrease in IRR from 47.3% to 45.9%.

2) Another solution is to increase the thermostat set point slightly, which activates the back-up heating assistance earlier. This effectively solved the problem as well, although care must be taken to increase the set point by not too big a margin. This can cause an unnecessary activation of the back-up heater during autumn and spring periods. An increase from the current thermostat set point (Refer to Appendix A) of $T^*_{set} = 0.55$ (38°C) to $T^*_{set} = 0.62$ (42°C) proved to be sufficient to solve the temperature deficiency in winter by activating the heater slightly earlier, without

unnecessarily activating back-up heaters during the remaining months. No noticeable decrease in IRR was experienced for this adjustment.

It was found from the simulations that hot water deficiencies never occurred after the set point adjustment was made. The resultant savings varied only within ±0.9% of the savings determined in the final optimization phase.

8.2 Tariff 2: 25kW heat pump and 60kW backup heater

The 25-year Monte Carlo analysis was also performed for the optimised Tariff 2 system. This optimised system included all the optimisation phases except for the multiple stage control of the back-up heater proposed in Section 5. It was found that the original back-up heating capacity of $Q^*=1.27$ (60kW) proved to be insufficient during some of the simulation cycles, resulting in the supply temperature dropping below the minimum required level of $T^*=0.8$. Increasing the back-up heating capacity from $Q^*=1.27$ to $Q^*=1.52$ (72kW) solved the temperature deficiencies. The IRR decreased slightly from 47.7% to 47.3% due to the higher initial cost of the increased back-up heater capacity. Resultant savings varied only within ±1.1% of the savings determined in the final optimization phase.

9 Comparative results between baseline system and optimized in-line heat pump system

The optimisation proposals that were evaluated in the previous sections resulted in a generic design guideline for the in-line heat pump system, based on both tariffs structures evaluated. A summary of these guidelines is provided in Appendix B. This section provides a summary of results that illustrates the main differences between the baseline system and optimised in-line heat pump systems developed in this study.

Operational cost

Firstly a summary of the reductions in operational cost is provided in Table 5. The 40kW heat pump system utilised in the Tariff 1 application realised a 68% reduction in operational cost. The 25kW heat pump system utilised in the Tariff 2 application realised a 53% reduction in operational cost.

Table 5: Operational cost for baseline system and optimised in-line heat pump systems

	Baseline system	**40 kW Heat pump system**	**25 kW Heat pump system**
Tariff 1	36.92 c/kWh (ZAR)	11.81 c/kWh (ZAR)	
Tariff 2	36.22 c/kWh (ZAR)		17.02 c/kWh (ZAR)

Energy efficiency improvement

A commonly used method for evaluation of energy efficiency improvements (IPMVP (2002)) is by plotting the baseline energy consumption against the improved energy consumption after the retrofit. Since the hourly electrical energy consumption varies significantly when viewed on a short-term basis, the results are presented by a moving average of the hourly data to avoid the graph becoming cluttered.

Figure 11 shows the 24-hour moving average of electrical energy consumption for a 30-day period, for the baseline system, 40kW heat pump system (Tariff 1) and the 25kW heat pump system (Tariff 2). It shows that all three profiles follow the same pattern, caused by the fluctuation of occupancy and hence hot water consumption. The electrical energy consumption of the two heat pump systems is however much lower when compared to that of the baseline system. The Tariff 1 heat pump system with a heating capacity of 40kW ($Q^* = 0.84$), generally consumed less electrical energy than the 25kW ($Q^* = 0.51$) heat pump system used in Tariff 2. This is due to the back-up heaters doing less heating work in the 40kW heat pump system when compared to the 25kW heat pump system, as discussed in Section 6. Energy efficiency was improved by 59% for the Tariff 1 system, and by 42% for the Tariff 2 system.

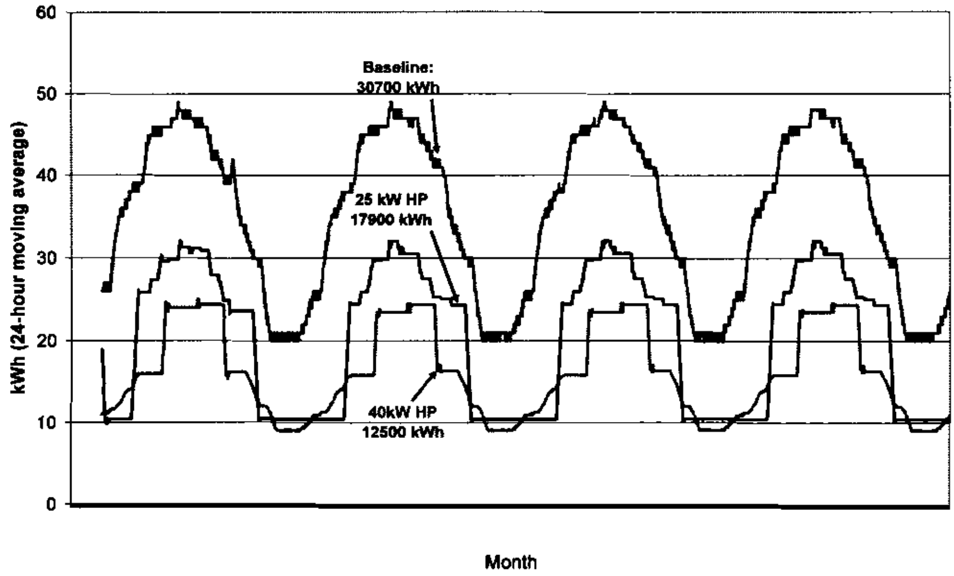


Figure 11: Energy baseline comparison

Maximum demand contribution

Figure 12 shows the monthly maximum demand contribution of the three systems for a year. In the case of the 40kW heat pump system, the MD contribution is reduced significantly, with the back-up heater only adding to MD during the 3 winter months of the year. In the case of the 25kW heat pump system the maximum demand contribution is much higher. This is however of no concern to the building owner, since peak demand is not charged for in the electrical tariff.

This leads to a discussion on the viability of this time-of-use tariff currently applied in the commercial building sector. The significant difference in electrical consumption cost between peak and off-peak periods encourages customers to avoid excessive use of electrical energy in peak periods. From techno-economic analysis it is however clear that the penalty involved in a high electrical demand contribution in peak periods is not severe enough to encourage customers to avoid it completely. If a high peak demand is encountered only a small number of times per month, the associated increase in operational cost is small when compared to a tariff where Maximum Demand is charged for. This might pose a problem for ESKOM in view of its DSM efforts. The general conclusion that can be made from this is that the application of time-of-use tariffs in the commercial building sector can actually be detrimental towards ESKOM's Demand Side Management efforts.

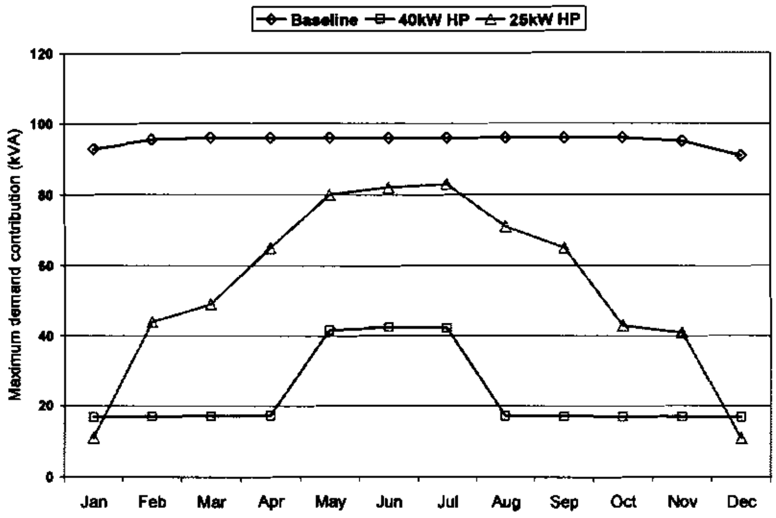


Figure 12: Monthly recorded peak demand for a year simulation

10 Conclusion

In this chapter we evaluated several proposals for the optimisation of commercial building sanitary water heating systems. This resulted in a system configuration for each electrical tariff that provides maximum economic potential compared to the baseline system, without compromising hot water availability. The design guidelines were then tested by a Monte Carlo analysis. Slight changes were made to keep design parameters within the design constraints. The resultant design guidelines are expressed in non-dimensional parameters, meaning that these results can be applied to different size systems in hotels, depending on the type of electrical tariff used. A summary of these guidelines are provided in Appendix B.

Results can be viewed from two points of view; utility and client. For any system operating on the typical commercial sector tariff that includes a MD charge (Tariff 1), the benefits of demand reductions are clear, and the utility can obtain significant DSM load shifting out of peak periods. Results did however show that an electrical tariff based on a time-of-use energy consumption schedule, which does not include a MD charge (Tariff 2), proves to be detrimental towards utility DSM efforts. Having a high electrical demand in the utility's peak demand periods is not penalised sufficiently by the time-of-use tariff. This also leads to some of the proposals described in phase 2&3 optimisations to be less economically viable or even decreasing IRR for a system subject to the time-of-use tariff.

Hotel owners can obtain significant cost savings with the implementation of the optimised in-line heat pump systems at their sanitary water heating facilities. Payback periods of less than 2.5 years are expected for systems on both tariffs analysed. This is based on an IRR of 47.1% for systems subject to Tariff 1 with a MD charge, and 47.3% for systems subject to Tariff 2, under current economic conditions.

CHAPTER 7 - A DAY-AHEAD DIGITAL CONTROL ALGORITHM FOR SANITARY WATER HEATING SYSTEMS SUBJECT TO REAL TIME PRICING

Abstract

Chapter 4 described the implementation of 34 in-line sanitary water heating systems at AngloGold Ashanti mine residences. Significant DSM load shifting was achieved to the benefit of ESKOM. While ESKOM benefits directly from this implementation in terms of DSM, the client only benefited partially due to the electrical load being shifted out of a typically expensive priced period in the client's Real Time Pricing (RTP) tariff. If sanitary water-heating loads can be controlled further to exploit the RTP tariff for the whole 24-hour period instead of just the 2-hour DSM period, the client can obtain additional savings. This can potentially increase client participation in utility funded DSM projects since they can be provided with direct cost benefits.

This chapter describes the development of a digital control model for sanitary water heating systems subject to RTP. This model attempts to optimise the cost efficiency of the water heating system without compromising hot water availability. The development of a default-heating schedule is described that uses historical data and the RTP price provided one day ahead of time. This heating schedule optimises cost effectiveness while still providing the required amount of heating. An intervention control model is also developed that intervenes in the heating schedule to avoid hot water deficiencies, while still being sensitive to energy pricing. These intervention decisions are based on measurements taken at the hot water storage facility. Additional control measures to further optimise cost effectiveness and reliability were also evaluated. This includes a master intervention control that prevents hot water run-out in case of extremely high hot water consumption, by activating the full installed heating capacity regardless of energy pricing. A digital switch-off control is also evaluated, which attempts to boost thermal storage before critical load shedding periods.

The algorithm was tested with the simulation program developed in Chapter 5. Results for a typical RTP profile showed a possible reduction of 20%-29% on operational cost when the digital control system is employed. Cost reductions are mainly a function of system utilisation: bigger non-dimensional heating and storage capacities result in higher savings potential.

Simulation results done for all the in-line heater systems installed at the Anglo Ashanti Mines described in Chapter 4, showed that an average reduction in operational cost of R26.70/MWh of thermal energy consumed is possible.

1 Introduction

Chapter 4 described the implementation of 34 in-line water heating systems at AngloGold Ashanti mine residences. These systems were configured to shift most of the water heating electrical load out of the utility critical period between 18:00-20:00 each day. No loss in hot water availability was suffered as a consequence of the load shifting. While the utility benefits directly from this implementation in terms of DSM, the client only benefited partially due to load being shifted out of a typically expensively-priced period on the client's Real Time Pricing (RTP) tariff. There is however significantly more potential for energy cost optimisation for the client. The potential for additional load shifting can be exploited by the in-line heating systems that shift heating load very effectively as illustrated in Chapter 4. The additional cost savings can be achieved if the daily required heating load can be programmed to optimise cost efficiency for the whole 24-hour period instead of only the 2-hour utility DSM period. This chapter addresses such a cost optimisation tool that can potentially increase client participation in utility funded DSM projects, by providing them with direct cost benefits.

2 The use of Real Time Pricing for DSM purposes

Real Time Pricing (RTP) has been used successfully by electrical utilities as a DSM tool. Previous studies [O'Sheasy (2002), Roos (1996), David *et al* (1986), Caramanis *et al* (1982)] showed that significant load shifting can be achieved for the electricity supplier during times of load constraints. Customers benefit due to cost reductions as well as increased production during times of low prices.

The term 'Real Time Pricing' is slightly misleading in suggesting that a continuously varying price is computed and supplied to customers in real time. In practice however, RTP is based on a short-term forecast of utility conditions. These forecasts can range from one hour to one week, with price levels fixed for short discreet time periods, typically one hour. The day ahead posting of hourly prices has been adopted as the industry standard (Schiess (1997), O'Sheasy (2002)). This is also the standard used by ESKOM in South Africa.

Since RTP varies daily, a control system is required that can respond to the price fluctuations, if a client is to obtain any savings benefit from the tariff structure. Previous studies [Schiess (1997)] have suggested the long term plotting of real time prices to determine the trends that drive the price of electricity. If a pattern emerges from these plots, a simple analogue control system with pre-set control measures can obtain a significant benefit from the tariff structure, although clearly not the most optimal benefit. Such an analogue system can also not respond to changes in system utilisation.

Large industrial consumers of energy that use RTP generally employs integrated energy management systems. These programs typically only control processes consuming large amounts of electrical energy. An example of this is given as the Gold Mining Industry in South Africa, where customers on RTP tariff attempt to control processes like gold smelting, hoisting, pumping, and air compression, all of which consume large amounts of electrical energy per process. Smaller electrical energy consumers like sanitary water heating systems at the mine residences are not controlled. The electrical energy consumption of each individual water heating system is relatively small when compared to the sizeable processes mentioned above. The total electrical energy consumption of all the water heating systems serving the large number of workers combined, is however comparable to the electrical consumption of a large process.

The need therefore exists for a control system that can be fitted on each of these sanitary water-heating systems. This system should allow automated decision-making based on pricing variables, as well as operational variables for the specific system. The potential accumulated savings that can be achieved by the sum of all these controlled water heating systems can provide significant financial incentive for the client. Several constraints are however present in developing such a control system. These constraints include the cost of implementation, which is typically related to the complexity of control. In order to obtain the maximum benefit from the pricing structure, a very complex control system might be required that in turn requires large and expensive computing power. However, if a large portion of the potential savings can be obtained using a simplified approach that will cost less to implement, the economic viability of the control system can be greatly improved. The control model should therefore be simple enough to be programmed onto a 'Programmable Logic Controller' (PLC). PLC's have proven to be a very cost effective and reliable method of control on industrial systems and processes (Salkintzis *et al* (1997), Rullán (1997), Gerkšič *et al* (2005)).

In this chapter the development of a digital control model is discussed, that can be installed at each of the in-line water heating systems. The simulation model developed in Chapter 5 will be used as the basis for the evaluation of this control model.

3 Requirements of the digital control system

The main purpose of the digital control system is to: *Minimize cost per kWh electrical energy consumed, but not at the expense of reliable hot water supply.*

In order to optimise the operation, a good prediction of system utilisation is required. The use of historical data to predict the water heating system behaviour is the only method available. A good prediction will however require that there are not large day-to-day fluctuations in hot water consumption. If the occupancy varies significantly in a random manner from day to day, no reliability can be associated with the predicted system utilisation derived from historical data. A good example of this is a hotel where the occupancy varies significantly from day to day in an unpredictable manner. In this case historical data would be unreliable for prediction purposes. A constant occupancy would be ideal for prediction purposes, or an occupancy that varies in a predictable manner. At the mine residences workers are present in constant numbers during the working week. Leave is also granted on a yearly rotational basis to ensure a constant working force throughout a year. Hot water consumption patterns can therefore be predicted with reasonable accuracy at these mine residence water-heating systems, where the digital control system can be implemented.

A prediction of system utilisation can then be used to predict an optimum heating schedule that satisfies the total heating requirements for a day. For reasons such as inclement weather conditions, day-to-day variations in the hot water demand is however still likely to occur. The predicted heating schedule also does not take the storage capacity of the system into account during calculations. This can cause hot water deficiencies to occur during the day due to insufficient thermal storage capacity. It is therefore clear that the control system should not rely solely on historically predicted data. There should also be provision for intervention control facilities that can override the predicted schedule in the case of hot water consumption pattern changes or insufficient stored energy. Since storage capacity also plays an important role during load shedding periods, and attempt should also be made to maximise the stored energy before load shedding periods. The following sections address the development of methods that can reduce operational cost without compromising hot water availability. A summary of the intended methods is as follows:

- Develop a Default Heating Schedule (DHS), which provides the optimum relation between cost and the amount of heating required. This is predicted from historical data and the RTP price profile provided one day ahead of time.
- Develop Intervention Control (IC) that attempts to provide an early intervention into system operation by incrementally adding heating stages to the DHS. This control therefore assists the DHS by attempting to provide good hot water availability, without completely compromising cost effectiveness.
- A Master override control is provided that overrides all heating control and activates the full heating capacity, to prevent hot water deficiencies in times of unexpected high hot water consumption.
- A Digital switch-off control is provided that boosts the amount of stored energy before a scheduled load-shedding period that occurs for DSM reasons or due to an expensive RTP period.

4 Developing a 'Default Heating Schedule' (DHS)

The main objective of the Default Heating Schedule (DHS) will be to provide a prediction of the most cost effective operation of the water heating system. Inputs are the RTP schedule for the following day, and historical data for system utilisation such as the total volume of hot water consumed per day, or electrical data. Figure 1 illustrates the basic approach of the DHS. It provides a heating schedule that is the inverse of the RTP profile for the 24-hour period.

This type of approach will allow the most heating to be done during lower priced periods, and the least heating during expensive price periods. The historical data for system utilisation is used to predict the amount of heating required in a 24-hour period. To filter out small day-to-day variations, the use of a moving average of historical data for a number of days before the calculation day is proposed.

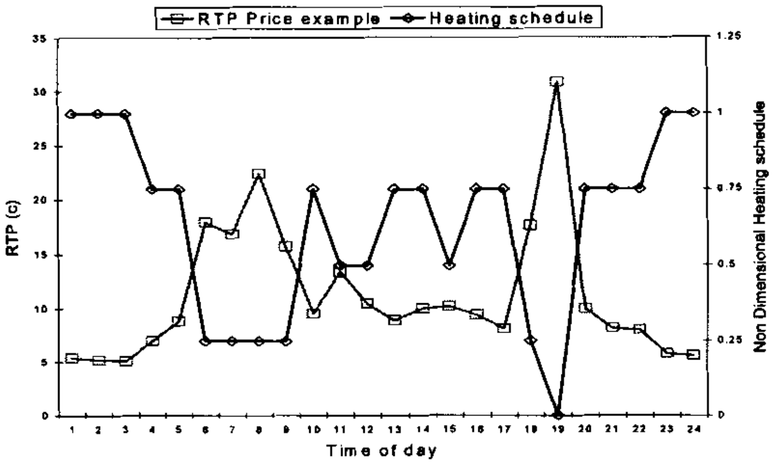


Figure 1: Heating Schedule determined as the inverse of the RTP price

There are two possible approaches for predicting system utilisation:

1. The use of historical thermal data obtained from temperature measurements and a volumetric flow meter.
2. The use of historical electrical data obtained from the heaters.

The use of thermal data is seen as the most accurate prediction method since it provides a direct measure of how the system is utilised. It is however a more complex calculation method, since heat losses from the system also need to be taken into account when the daily required heating is predicted. Another concern is the reliability and accuracy of a volumetric flow meter. A volumetric flow meter is susceptible to fouling in the water pipe lines. This assessment is based on experience gained during implementation of in-line heating systems as described in Chapter 4.

Electrical data from the heating equipment already includes the heating required to overcome heat losses from the system. It is therefore a simpler calculation method when compared to the use of thermal data. Electrical data however does not provide a direct measure of how the system is utilised, but rather gives a time delayed indication. Heating energy is generally delayed in time compared to hot water consumption due to the thermostat dead band and fluctuations in hot water consumption. Further delays are also caused by the way heating was scheduled during the previous days for varying RTP prices. These time delays that can vary from day to day can cause errors in predicting what the required heating in an exact 24-hour period should be.

The best theoretical accuracy should be obtained when thermal data is used. A decision on which type of data to use for prediction purposes should however take into account the reliability and accuracy of the instrumentation installed at the specific site. For sake of completeness, this study provides calculation methods for both approaches.

4.1 Predicting the required amount of heating

Using historical thermal data

The use of thermal data requires temperature measurements at the inlet and outlet of the water heating system, and a volumetric flow meter, which measures all the water entering the system. The amount of thermal energy consumed by the users is calculated as follows:

$$F_i = V_{i,c} \cdot c_p \cdot \rho_{water} \cdot (T_{i,outlet} - T_{i,inlet}) \qquad [\,J\,] \qquad \text{Eq 1}$$

$V_{i,c}$ represents the volume of water consumed during a time step. $T_{i,inlet}$ and $T_{i,outlet}$ are inlet and outlet temperatures of the water heating system respectively, as measured during a time step.

The total energy consumed for a 24-hour period with *n* time steps would then be

$$F_{total} = \sum_{1}^{n} F_i \qquad [\,J\,] \qquad \text{Eq 2}$$

Eq 2 accounts for the total daily amount of hot water consumed. Heat losses from the water heating facility also need to be included before the required amount of heating can be predicted. Heat losses occur only from the storage tank facility. No ring main circulation system is utilised at the mine residence sanitary water heating facilities, therefore no ring main heat losses are present.

The heat loss from the storage tank is a function of the average temperature difference between stored water and ambient, as well as the thermal insulation properties of the system. The temperature differences between stored water and ambient are calculated during each time step in the simulation program. This data will however not be available in practice on the actual water heating system. Since the digital control system needs to operate at an actual water heating system without the aid of the simulation program, a different approach for determining heat losses is required.

For fixed thermal properties, the heat losses are mainly a function of the temperature difference between stored hot water and ambient. The average stored water temperature can be approximated from the system characteristics, i.e. by the amount of hot water consumed, heating capacity and storage capacity. This is illustrated in Figure 2 that shows the fraction of heat losses of the total amount of heating required per day, for different non-dimensional heating capacities (Q^*) and non-dimensional storage capacities (V^*). (Definitions of non-dimensional parameters are provided in Appendix A). These results have been determined using the simulation program developed in Chapter 5. An assumption is made that all the water heating systems comply with the standards for thermal insulation as provided by ASHRAE (2003). The hot water consumption profile for mine residences as obtained in Chapter 2 has been used.

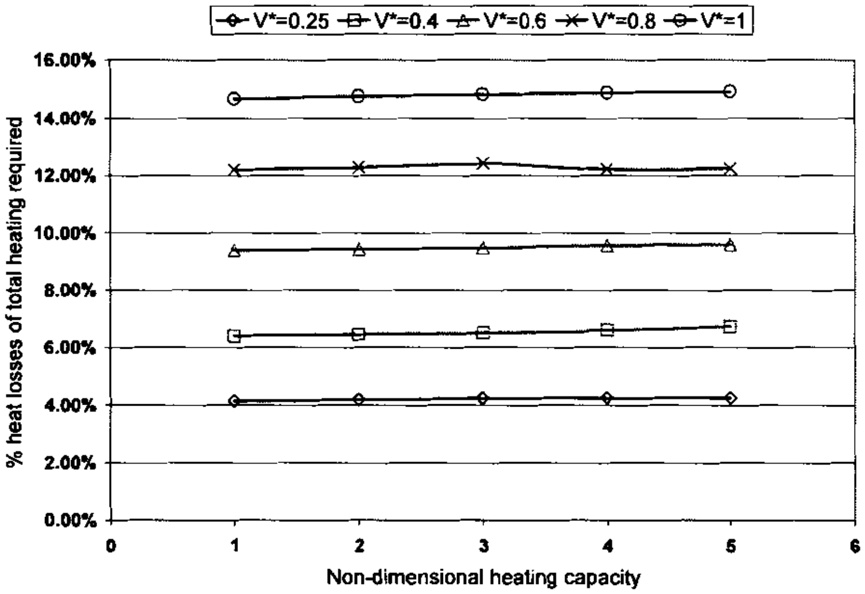


Figure 2: Heat loss fractions for different Q^* and V^*

From Figure 2 it can be seen that the heat loss fraction is mainly a function of V^*, with heat losses increasing significantly for higher V^*. The heating capacity available at the water heating system will also have an influence, since it determines how close the water temperature in the storage tank is to the set-point value throughout the day. In Figure 2 however the heat losses only increase marginally for increasing Q^*. This is mainly due to the relatively flat water consumption profile at the mine residences with very few peaks and troughs. Due to the relatively flat hot water demand profile, the average tank temperature should not deviate significantly from the set-point value, not even for smaller non-dimensional heating capacities. This correlates well with results obtained in Chapter 2 that investigated the influence of hot water consumption profiles on system design parameters.

From these results, a loss fraction can be approximated as a function of Q^* and V^*. Since the purpose of the calculation process is to determine a value for required heating (Q^*), it is not known at this stage. An initial value for non-dimensional heating capacity $Q^*_{initial}$ is calculated in Eq 3.

$$Q^*_{initial} = \frac{F_{total}}{P_{plant} \times 3600 \times 24} \qquad \text{Eq 3}$$

with P_{plant} the total installed heating capacity of the plant.

The heat loss fraction is now approximated by an empirical equation provided in Eq 4, based on the results shown in Figure 2. The results are valid for systems with standard insulation properties, and for $1.1<Q^*<5.0$ and $0.2<V^*<1.0$.

$$K_{loss} = 0.0014 \times Q^*_{initial} + 0.1462 \times V^* \qquad [\,\%\,] \qquad \text{Eq 4}$$

This heat loss fraction is expressed as a fraction of the total energy requirement per day. Since the thermal energy consumed by the system users represents the remaining fraction of the total, the heat losses can be expressed as a function of thermal energy consumption.

$$E_{loss} = F_{total} \cdot \left(\frac{K_{loss}}{1-K_{loss}}\right) \qquad [\,J\,] \qquad \text{Eq 5}$$

Q^{*} is now determined from the following equation.

$$Q^{*} = \frac{F_{total} + E_{loss}}{P_{plant} \times 3600 \times 24} \qquad \text{Eq 6}$$

This value for Q^{*} is now provided as the new $Q^{*}_{initial}$ value. The calculations done in Eq 4 to Eq 6 is now repeated until $Q^{*}_{initial}$ approximates Q^{*} to within 2%.

The total amount of heating hours required per day, at full heating capacity, can then be calculated as follows:

$$Heatinghours = 24 \times Q^{*} \qquad \text{Eq 7}$$

Using Historical electrical data

The use of electrical data requires metering that can log the electrical consumption of the heating equipment at the plant. These measurements are typically logged on a basis of 30-minute or 60 minute intervals. For prediction purposes, the total amount of electrical energy consumed per day needs to be available from the data. The moving average of at least five days of daily consumption is then provided to the DHS as the total daily electrical energy consumption (kWh_{day}). The total amount of heating hours required per day is then calculated as follows.

$$Heatinghours = \frac{kWh_{day}}{P_{plant}} \qquad \text{Eq 8}$$

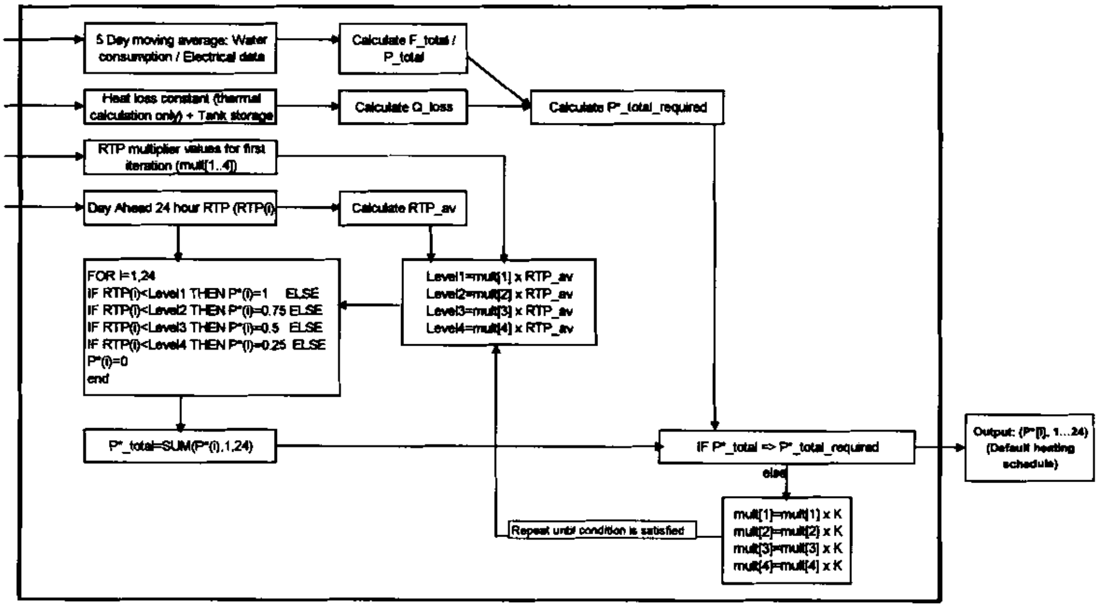
4.2 Calculating the DHS

With the amount of heating hours required per day now known, the next step would be to spread the required heating in the most cost efficient way throughout the day. The basic philosophy is to calculate an average RTP price from the provided 24 hour-prices. This is then used to determine whether energy cost for a specific hour is below or above the average price, which would basically indicate where heating can be scheduled for the most cost effective operation.

The philosophy is refined further by settings different RTP price levels as a function of the average RTP price. The number of levels will depend on the number of control stages that the heater can be divided into.

Each level will allow a certain number of heating stages to be activated. For instance; a RTP price below a very low cost level will allow all 4 stages in a 4-stage heating system to operate, while a slightly higher price but still below the following price level will allow only three heating stages. This selection process continues to where a very high price will allow only one stage to operate, or even suggests complete load shedding. Once this calculation is complete, the total heating *allowed* for the day is calculated as the sum of the hourly scheduled heating and compared to the total heating *required* (Eq 7). This calculation loop is then repeated until the heating *allowed* equals or exceeds the heating *required*, by increasing the RTP price levels incrementally after each calculation until the condition is satisfied. The chosen RTP price levels for the first calculation are very low, which will effectively allow heating to be done only during low price periods in the case of a heating system with a large non-dimensional heating capacity. Small increments for increasing the RTP price levels after each calculation are then used to enhance the accuracy of the predicted schedule.

The approach in determining the Default Heating Schedule is shown diagrammatically in Figure 3.



```
FOR I=1,24
IF RTP(i)<Level1 THEN P*(i)=1    ELSE
IF RTP(i)<Level2 THEN P*(i)=0.75 ELSE
IF RTP(i)<Level3 THEN P*(i)=0.5  ELSE
IF RTP(i)<Level4 THEN P*(i)=0.25 ELSE
P*(i)=0
end
```

Figure 3: Control algorithm determining the Default Heating Schedule

4.3 Examples of DHS calculation

The following examples are provided to illustrate the effectiveness of the calculated Default Heating Schedule in providing the best energy cost profile for the required amount of heating. In Figure 4 the total 'heating hours' required per day are 8 hours, which can also be expressed as a non-dimensional heating capacity of $Q^*=3.0$. In Figure 5 the 'heating hours' required per day are 15 hours ($Q^*=1.6$), and in Figure 6 the heating hours required are 22 hours ($Q^*=1.09$). All three examples use the same RTP 24-hour price profile, as shown in the graphs. The RTP price levels are increased by a multiplier of K=1.02 after each calculation until the total *required* heating is achieved.

In Example 1, shown in Figure 4, the heating system is scheduled to switch off completely during the more expensive hours. It also operates on only 25% capacity during most of the hours in the middle of the day where the RTP price is slightly lower but still higher than average. Most of the heating is done during the periods when the RTP price is very low.

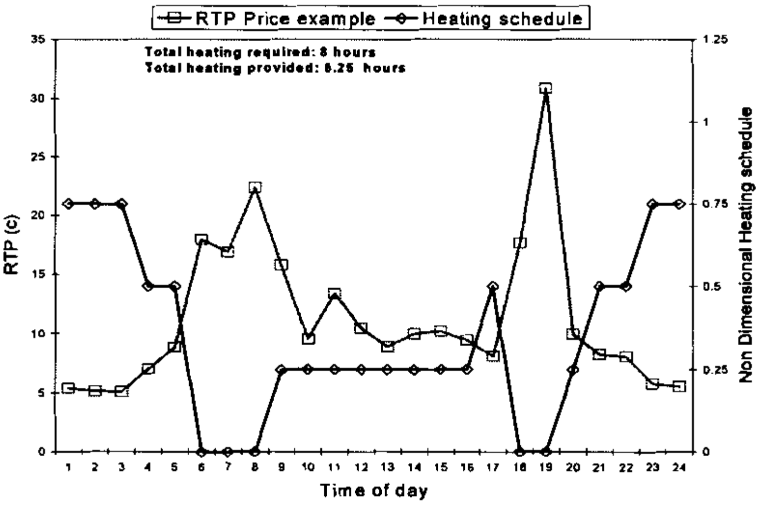


Figure 4: Example 1 – $Q^*=3.0$

In Example 2, shown in Figure 5, the required heating hours is almost doubled when compared to Example 1. This leads to more heating stages being activated during most hours. The heating load is however still being shed completely at 19:00 during the very high price peak at that hour.

Example 3, shown in Figure 6, illustrates that the rather constraint heating capacity of the system is required to operate for most of the day. This leads to the heater being operated at full capacity for most of the day, with only partial load shedding during the most expensive RTP price hours. It is however clear from all the graphs that the algorithm proposes the most economic heating schedule while still achieving the required total amount of heating.

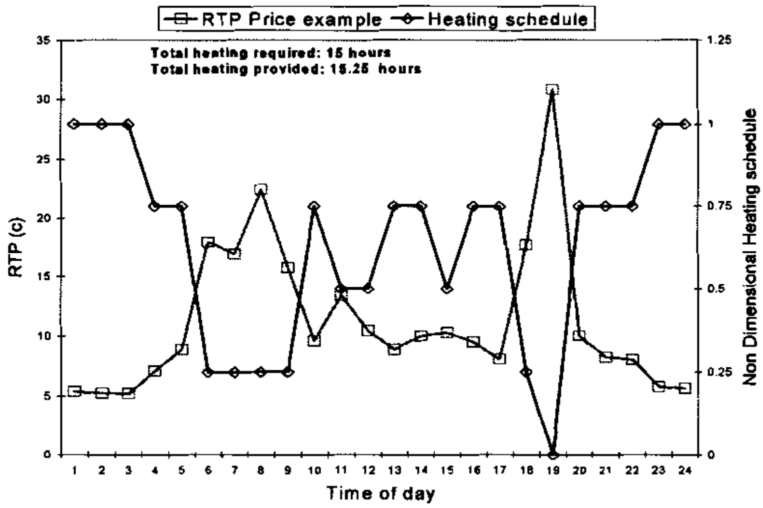


Figure 5: Example 2 - Q^*=1.6

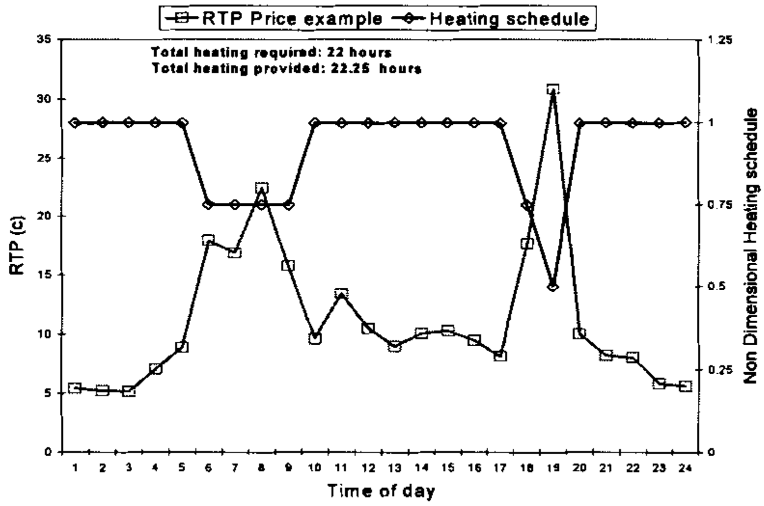


Figure 6: Example 3 - Q^*=1.09

5 Intervention Control (IC)

The Default Heating Schedule developed in the previous section will provide the best operational cost for the water heating system. There are however a number of variables involved in the operation of the water heating system that can cause differences between the proposed heating schedule and actual heating demand.

- The 'Default Heating Schedule' is determined without taking into account the profile in which hot water is consumed during a 24-hour period, or the storage capacity of the plant. This means that some intervention measurement indicating that stored energy is at risk of being depleted during certain times of the day is required.

- A significant change in the amount of hot water consumed can occur from one day to the next. Even if the occupancy is relatively constant, events such as inclement weather or social events could cause a significant fluctuation in day to day hot water demand.
- As mentioned in Section 4, the volumetric flow meters used during the DHS calculation can fail to provide accurate measurements. If care was taken with the choice of equipment and the correct installation thereof, this should not happen on a regular basis. The possibility of malfunctions should however be taken into account, and since it can cause the DHS to be determined incorrectly, intervention into the heating schedule is required.

It is clear from these possible scenarios that some form of intervention control needs to be incorporated into the digital control model, since the predicted heating schedule can cause hot water deficiencies during the day. The following section discusses a number of options for intervention control.

5.1 Different measurement alternatives for intervention control

Temperature measurements

Intervention can be made by reacting upon measured temperatures at different levels in the storage tanks. Since the in-line heating method promotes thermal stratification in the tanks, a temperature sensor installed at a certain position in the tank can detect a significant change in temperature that would indicate the presence of the thermo cline region at the sensor, as described in Chapter 5. Certain predefined control measures can now be taken based in temperature-state and/or temperature-gradient measurements.

The use of temperature gradient measurements alone proves to be risky, given the fact that temperature change only occurs in sections of the storage facility where hot and cold water are mixed. When storage energy is depleted, only cold water will be moving past the sensor, and very little or no temperature gradient will be measured. This will therefore give no indication of the true state of the storage facility at the measurement point if only temperature gradient measurements are used.

The proposed option would be to combine the use of temperature-state and temperature-gradient measurements, allowing control with less risk than using only temperature-gradient measurements. It also provides more options than using temperature-state measurements alone. The problem in practice is that only a limited number of storage tank pockets are available for sensor installation. The limited measurement points can however be exploited to the full by taking both temperature state and –gradient measurements. The proposed method is discussed in more detail in the following sections.

Thermal calculations

Another option to determine the status of the storage facility might be through the calculation of the thermal energy in the tank by using the simple thermal equation $Q=m.Cp.\Delta T$, and doing a simplified first law analysis. Mass flow will be measured by a volumetric flow meter, and inlet and supply temperatures of the system will be measured with temperature sensors. This is however the same measurement equipment used to calculate the DHS, and is therefore susceptible to the same possibilities for erroneous calculation, as discussed earlier. It would therefore be very risky to let intervention control rely on the accuracy of the flow meter, since the intervention control forms by figure of speech, the 'last line of defence' against hot water deficiencies. Using thermal calculations in the intervention control is therefore not recommended.

Based on the above discussions, it is decided to make use of a combination of temperature-state and temperature-gradient measurements. This decision is evaluated in terms of the best achievable accuracy by also taking into account the reliability of the method when actual equipment is used in practice.

5.2 Positioning of temperature sensors

As mentioned earlier, only a limited number of storage tank pockets will be available for the installation of the temperature sensors. The reason for this is that most of the tank pockets are typically used for thermostats and safety equipment, all contributing to the main control of the system. For this reason it is decided to make use of three temperature sensors installed as close as possible to the bottom, middle and top of the storage tank facility. The main purpose of each sensor is described shortly.

a) Temperature sensor installed near the bottom of the tank ($h^*=0.0$)

This sensor will determine whether the system is at the set-point temperature and should be switched off. This can be however be done by a simple thermostatic switch. The reason for using a temperature sensor in the digital control system would be to allow variations in the switch-off set point. This method will be discussed in detail in section 6.2.

b) Temperature sensor installed near the middle of the tank ($h^*=0.5$)

This sensor plays an important role in intervention control since most of the dynamic temperature changes in the storage tanks occur somewhere in the middle of the tank during normal operation. Most of the intervention will be done based on feedback from this sensor. For instance, a decrease in temperature during a time step in the middle of the tank will indicate that the rate of hot water consumption is higher than the rate of hot water supplied by the in-line heater. In addition to this, it indicates that only half of the stored energy is left, which might prompt the system to activate more heating stages. This method will be discussed in detail in section 5.4.

c) Temperature sensor installed near the top of the tank ($h^*=0.9$)

When water temperature drops below a certain value at this sensor, it indicates that most of the stored energy is consumed, and that hot water deficiencies can occur. This sensor therefore provides an overriding control that activates maximum heating capacity regardless of energy pricing, to avoid hot water deficiencies. This method will be discussed in detail in subsection 6.1.

5.3 Calculating the temperature-state and temperature gradient values

Temperature gradient

As mentioned in the previous paragraph, a negative or positive temperature gradient indicates whether the hot water consumption rate is higher or lower than the rate of hot water supplied by the heater. It is important to mention though that this type of indication is only true in the case of the improved in-line heating configuration where thermal stratification exists. It will not be valid in a conventional in-tank heating system, since the activation of the in-tank heater destroys any stratification that might have been present during a load shedding period. This can even lead to a decrease in temperature at a certain level caused by mixing effects, and can even happen while the rate of energy added is higher than the rate of energy consumed at that time.

In the in-line heating configuration the instantaneous temperature gradient at any given time can change rapidly between negative and positive, since it depends on the instantaneous amount of hot water consumed. If the real-time temperature gradient is used for intervention control, these rapid gradient changes might lead to continuous switching of stages. It is therefore recommended that intervention be calculated on a time step basis, based on the average temperature gradient calculated for the whole of the previous time step.

Temperature state

The temperature at the end of a time step will be measured, and this value will be used for the intervention decision of the following time step. This single value for a time step will be used since the temperature can easily fluctuate around a set point value, leading to continuous switching of heating stages. This scenario is normally addressed in thermostats by employing a temperature dead band between switch-in and switch-out. The required dead band in this case will however be obtained by the time delay of using only one temperature measurement per time step.

Intervention time step

The correct choice of time step length is very important to obtain the desired intervention control. The purpose of the intervention control is to correct the system operation before any hot water deficiencies can occur, by reacting on current system usage patterns and the state of the storage facility. The optimal solution would therefore be to have real-time intervention control that can react directly to current conditions. As discussed however in the previous paragraphs, real-time intervention can cause a continuous switching of heating stages. For this reason a time step length is required that provides the best trade-off between system response and switching of heating stages. A time step of 7½ minutes is chosen, providing good intervention control response without increasing the typical amount of switching in the system per contactor.

5.4 Intervention control algorithm

The basic principle behind the Intervention Control should be to avoid hot water deficiencies, but without completely sacrificing the cost effectiveness of the system provided by the Default Heating Schedule. This section describes an algorithm that incrementally adds heating stages according to a set of criteria, while still being sensitive to the energy pricing profile. As described in the previous paragraphs, only one intervention control decision is taken per time step.

- Scenario 1: Temperature in the middle of the tank ($h^*=0.5$) at the end of the previous time step is *above* a chosen set point value, for instance 40°C. This is a satisfactory condition with typically more than 50% of the stored energy available, and no intervention is required.
- Scenario 2: Temperature in the middle of the tank ($h^*=0.5$) at the end of the previous time step is *below* 40°C but still *above* a second lower set point value, for instance 25°C. In addition to this, the average temperature gradient for the previous time step was *positive*, i.e. increased. This indicates that less than 50% of the stored energy is left, but also that the rate of hot water consumption is lower than the rate of water heating supplied by the heater. Since the system is coping with the current hot water demand, only 25% heating (one stage in a four stage heating system) is added in order to boost the storage capacity before possible periods of high RTP prices.
- Scenario 3: Temperature in the middle of the tank ($h^*=0.5$) at the end of the previous time step is *below* 40°C but still *above* the second set point value of 25°C. In addition to this the average temperature gradient for the previous time step was *negative*, i.e. decreasing. This indicates that less than 50% of the stored energy is left, and that the rate of hot water consumption is more than that supplied by the heater. This implies that a significant amount of hot water is currently being consumed, or that the DHS provided for too little heating to take place. This should prompt the system to add 50% heating to the default heating schedule, to avoid possible storage capacity deficiencies during periods of high hot water demand or high RTP prices.
- Scenario 4: Temperature in the middle of the tank ($h^*=0.5$) at the end of the previous time step was *below* the second set point value of 25°C. This implies that the stored thermal energy dropped well below 50% of the maximum. In this case an additional 25% heating is added to both scenario 2&3, i.e. 50% heating added for a *positive* temperature gradient, and 75% heating added for a *negative* temperature gradient.
- Scenario 5: Temperature at the sensor installed at the top ($h^*=0.9$) drops below a set point value of 40°C, indicating that less than 10% of the stored thermal energy is left. This will prompt the system to add 100% of heating to avoid hot water deficiencies. This control measure is called master override control and is discussed and illustrated in Section 6.1.

This proposed algorithm is shown schematically in Figure 7.

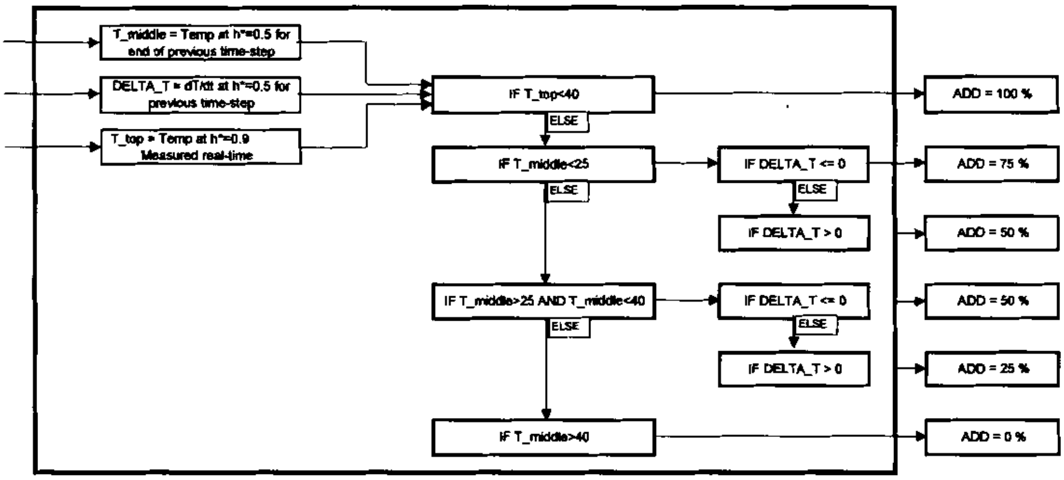


Figure 7: Schematic illustration of Intervention Control logic

6 Additional control measures to maximize cost efficiency and system reliability

This section evaluates control measures in addition to the DHS and intervention control. The aim of these additional control measures is to further improve cost effectiveness of the system as well as improving reliability in terms of hot water availability.

6.1 Master Override Control

In Chapter 1 the importance of a reliable hot water supply is emphasized. The intervention control attempts to address this, but to reduce the risk even further, it is proposed to have a real time master override mechanism to prevent hot water run-out. This mechanism will override all digital control signals and activate maximum heating capacity when there is an imminent risk of hot water deficiencies. The temperature sensor installed near the top of the storage facility will activate this override when typically 10% of the storage capacity is left. This control measure has also been utilized in the plants as described in Chapter 4, to prevent hot water deficiencies during the DSM load shed period. The difference between the master override control and intervention control is that the master override decision can be made in real time, whereas the intervention control decisions are made only at the beginning of a time step. The master override control will also activate the full heating capacity regardless of energy pricing, while the intervention control is still sensitive to energy pricing by incrementally adding heating stages.

An example day where the master override mechanism is utilised is provided in Figure 8. A load shedding signal was applied to the system from 16:00-20:00. A master override thermostat or temperature sensor is placed at a height of $h^*=0.9$ in the tank with a set point of 45°C. It can be seen that the heating system was activated before 20:00 at approximately 18:40, to avoid complete run-out of stored hot water.

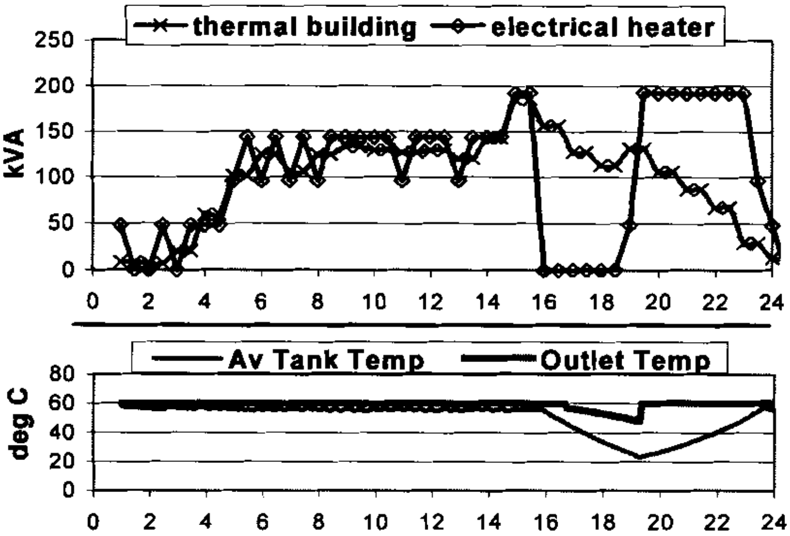


Figure 8: Illustration of Master Override Control

On the bottom graph in Figure 8 the outlet temperature and average temperature of the system is shown. The average temperature in the tank dropped to as low as 21°C before the heaters were activated, but the outlet temperature remained higher than 47°C. This indicates first of all that most of the stored energy remaining in the tank is concentrated at the top of the storage facility near the hot water supply outlet due to stratification. It also indicates that only a small fraction of the total thermal storage capacity is left, as seen by the small difference in the average tank temperature and the system inlet temperature of 15°C. The full heating capacity of the in-line heater is therefore activated which results in an almost instantaneous increase in hot water supply temperature. This happens even though the average stored water temperature is not increased immediately.

This illustrates the effectiveness of the master override control when used in conjunction with the improved in-line heating configuration. Even with very little stored energy left in the storage tanks, the end-user still had sufficient hot water and a hot water deficiency was effectively avoided. This control can therefore improve the reliability of hot water supply, although the cost effectiveness of the system can be compromised. This will be illustrated in the first case study in Section 7 of this chapter.

6.2 Digital system switch-off control

In the in-line heating configuration a thermostat or temperature sensor situated near the bottom of the storage tank normally controls heater operation. This will also be true in the digital control system, since no further heating, even if scheduled by the DHS, is required when the storage tanks are filled with hot water. The thermostat set-point is usually 5-10°C below the in-line heater outlet temperature set-point. This difference is required since it controls the inlet temperature to the heater in this configuration, and should therefore allow a certain minimum temperature rise through the heater. The set point is therefore typically 55°C when the heater outlet temperature is 60°C, which allows a 5°C temperature rise through the heater with the thermostatic control valve fully opened allowing maximum water flow.

If the thermostat set point is however increased to 65°C, the heater outlet temperature, although still normally controlled at 60°C, will rise to 70°C when the heater inlet temperature is allowed to rise to 65°C just before the system switches off. More energy can be stored in the storage tanks by doing this, although fluctuations in the outlet temperature of the system might occur. This increase in switch-off set point can however be used to enhance the stored energy content above the normal maximum amount just before a scheduled load shedding period.

To illustrate this effect, the same example used to illustrate the master override intervention (Figure 8) is used, but the system switch-off point is increased from 55°C to 65°C from 14:00 to 15:59. The result is shown in Figure 9.

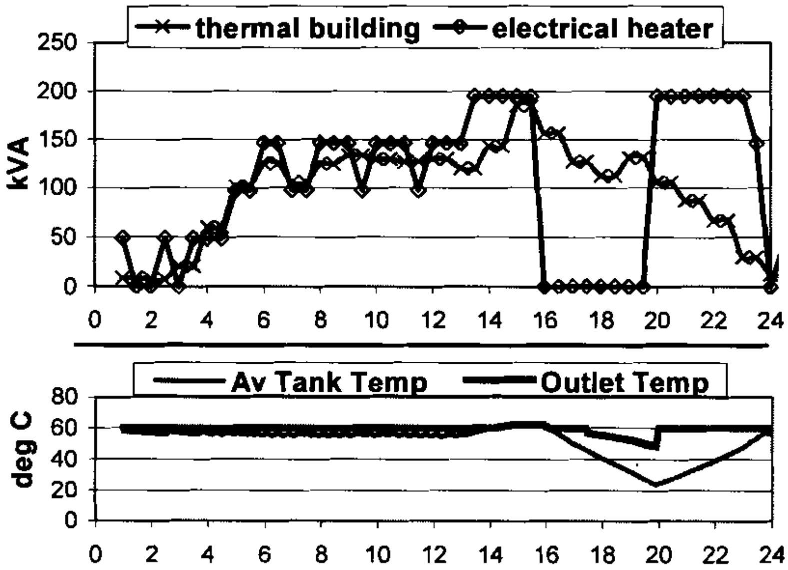


Figure 9: Digital system switch-off control increasing load shedding efficiency

From the graph it can be seen that the average and outlet temperatures of the system are increased above 60°C just before the load shedding period (16:00-20:00) occurs. The average temperature and outlet temperature again dropped to 21°C and 47°C respectively during the load-shedding period, which is the same as in the previous example. This is to be expected, since the same master override control is utilised. The activation of the heaters was however delayed by an additional 50 minutes from 18:40 in the previous example to 19:30 in this case. The load shedding period of the system was therefore increased. This clearly illustrates the effectiveness of using a digital temperature sensor allowing variations in set-point, instead of using a thermostat with only a manually adjustable set-point.

7 Results: Illustrative examples

This section provides simulation results where the proposed digital control system is utilised. The system consists of the Default Heating Schedule (DHS) described in section 4, and all the intervention controls described in section 5 and section 6. Figure 10 shows the RTP profile that will be used in all the examples.

Case studies representing realistic scenarios will be used instead of presenting results completely in generic form, due to the large number of variables involved, such as the hourly variations in the RTP profile. All the systems simulated are in-line heater systems as described in Chapter 4. Operational costs will be presented in terms of cost per thermal unit of energy consumed by the users (c/kWh).

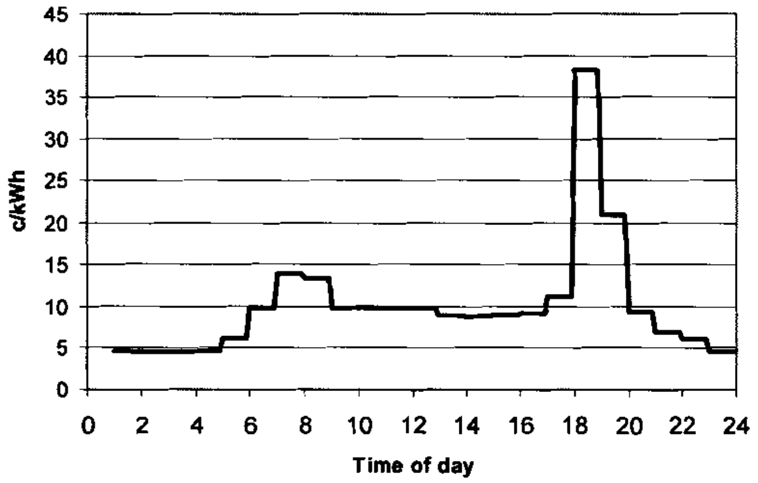


Figure 10: RTP price profile used in example studies

7.1 Example 1: System with $V^*=0.33$ and $Q^*=3.0$

The first example focuses on each individual part of the digital control system and the effect that it has on the operation of a water heating system. The cost savings provided by the Default Heating Schedule is illustrated, but also the need for Intervention control and the added advantages of digital switch-off control.

7.1.1 System without digital control

A system with a 192kW electrical resistance in-line heater, 10000-liter storage capacity with an average daily hot water consumption of 30000 litres at 60°C is used in this example. Hot water is consumed according to the mine residences profile as provided in Chapter 2. The system uses normal thermostatic control with no digital control system. Figure 11 shows the simulated electrical profile and the hot water consumption profile by the users expressed as thermal kilowatt (kW) on the top graph. The bottom graph displays the system's average and supply temperatures calculated by the simulation.

The system provides sufficient heating throughout the day with a constant hot water supply temperature throughout the day. The operational cost of this system for a 30-day period, based on the provided RTP profile, is R5007.75. The amount of thermal energy consumed by the users from this system in the 30-day period was 46694 kWh. The specific operational cost is therefore 10.72 c/kWh.

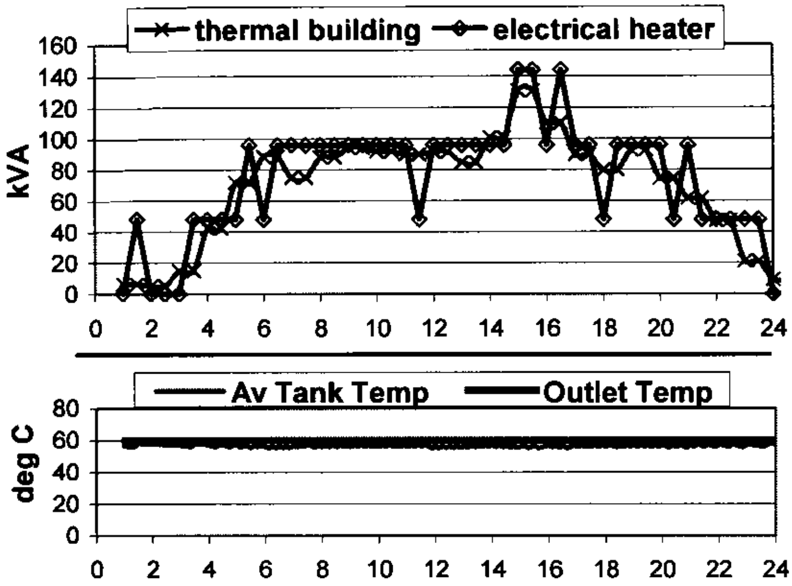


Figure 11: Example 1- 24 hour electrical, thermal energy consumed by users and temperature profiles for the system without digital control

7.1.2 System with DHS but without intervention

Figure 12 shows the operational profiles for the same system, but the Default Heating Schedule is now calculated and utilised. For this example however no intervention and overriding controls are utilised. It can clearly be seen that hot water supply is compromised, especially during the period when the very high RTP hour prices caused the DHS to schedule complete load shedding. Most of the stored thermal energy was consumed during this period. This can be seen by the supply temperature dropping to 22°C and the average tank temperature dropping to 15°C just after the load shedding period. The in-line heater now supplies hot water directly to the users when it starts to operate at 19:00, but only a fraction of the amount of hot water required by the users. This can be seen by the thermal consumption profile ('thermal building' in the graph) dropping lower between 19:00-21:00 when compared to Figure 11.

From these results it is clear that the DHS cannot be used without the assistance of some form of intervention control. The thermal energy produced was 45775 kWh, which is 920 kWh less than the baseline system. This is due to most of the thermal energy in the system being used up between 19:00-

21:00, as mentioned earlier. The controlled system should under all operational circumstances be able to produce the same amount of thermal energy as the baseline system, for it to be considered a viable control method.

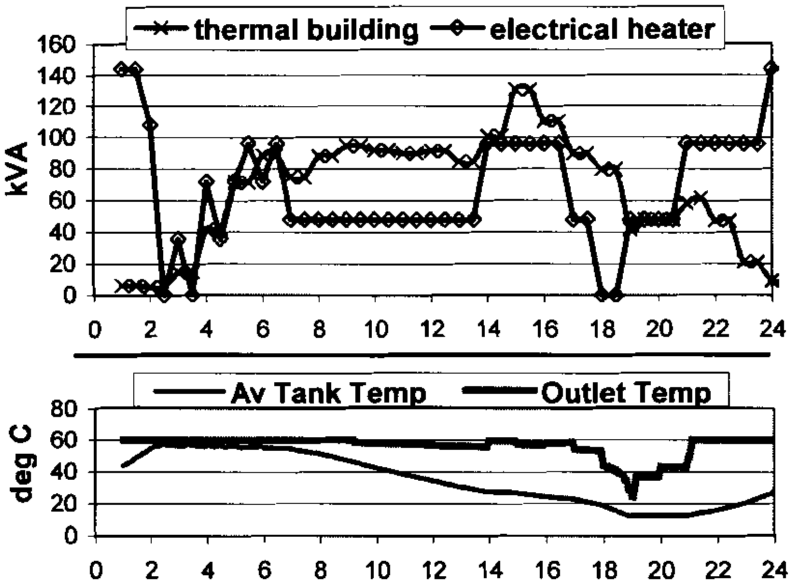


Figure 12: Example 1- System with DHS control but without intervention controls

7.1.3 System with DHS, with only master override intervention

The following simulation was done for the same system utilising the calculated DHS, but with the aid of only the Master Override Control as described in section 6.1. Figure 13 shows the resulting operational profiles. From the temperature profiles it can be seen that temperature deficiencies were avoided, with the system supply temperature never dropping below 50°C. This was achieved by the Master Override Control being activated when the thermal energy dropped below 10% of the total storage capacity. This happened at 17:45 and lasted until 18:45. The Master Override Control was therefore activated during an expensive RTP period, with a negative effect on the cost savings potential of the system.

This example produced a valid result since the system was able to produce the same amount of thermal energy as the baseline system. Operational cost was reduced to 9.79 c/kWh, which is 8% less than the system employing basic analogue control. This result clearly indicates that earlier intervention into the system operation is required, to avoid the full heating capacity to be activated during a potentially expensive price-period. The intervention control proposed in section 5 can provide intervention into the DHS by incrementally adding heating stages instead of abruptly adding the full heating capacity. This is illustrated in the following example.

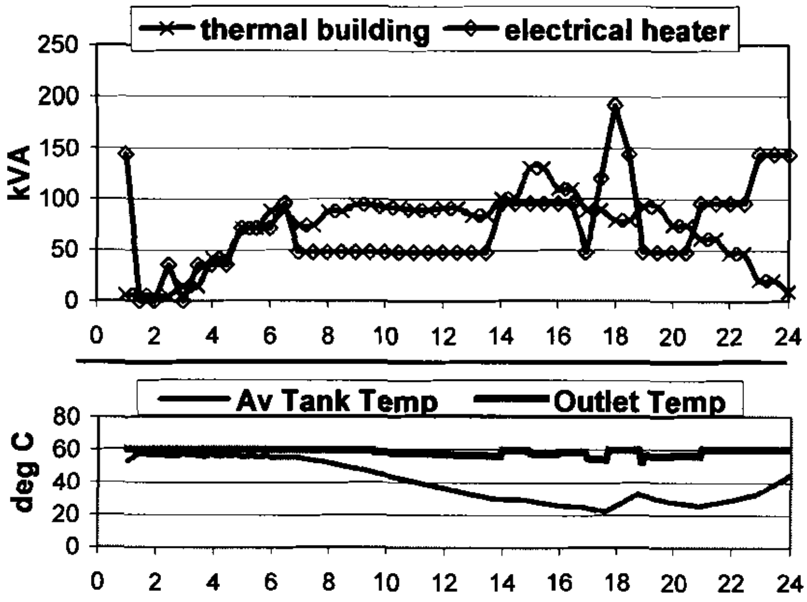


Figure 13: Example 1- System with DHS and Master Override Control

7.1.4 System with DHS and with intervention control

The following simulation was done for the same system using the calculated DHS, but now with the aid of Intervention Control as described in section 5. Figure 14 shows the resulting profiles.

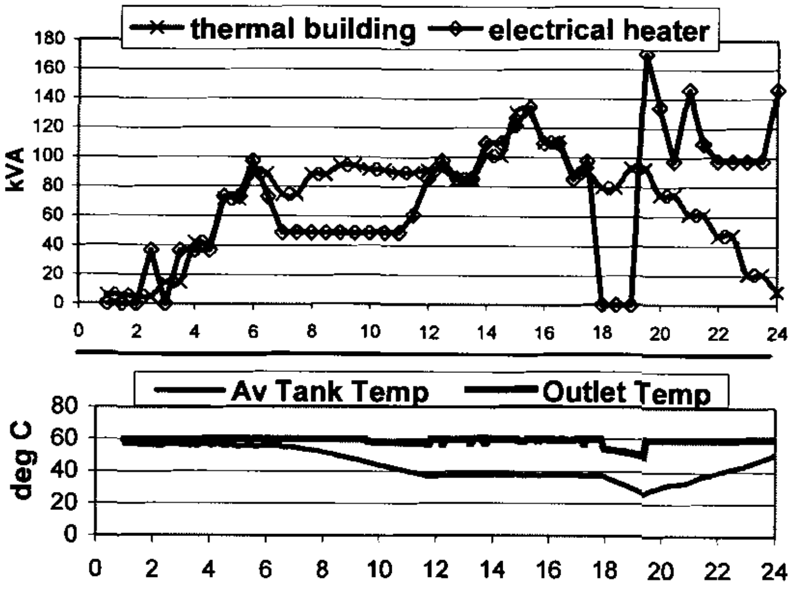


Figure 14: Example 1- System with DHS and Intervention Control

Temperature deficiencies were avoided with the minimum supply temperature always above 50°C for the simulation period. The thermal energy in the tank was kept at a level that allowed complete load shedding from 18:00 to 19:00, which is the most expensive RTP price hour. The load was also shed partially during 19:00-20:00, which is the second most expensive RTP hour during the day. The operational cost for this system was reduced to 8.09 c/kWh, which is a 24.5% reduction in operational cost compared to the analogue system. This is a significant improvement in cost efficiency when compared to the previous example where only Master Override Control was utilised together with the DHS.

7.1.5 System with DHS, with intervention control & digital system switch-off control

As a last refinement to the system operation, the digital system switch-off control discussed in Section 6.2 is added to the control system. The digital system switch-off control is implemented by the DHS before any complete load shedding periods, in this case the expensive RTP period between 18:00 and 20:00. This control will however only be allowed if the period in which it is done is not an expensive RTP period itself.

Figure 15 shows the resultant profiles. In a three hour period before 18:00 the full heating capacity is activated, and the average and outlet temperature of the system is now raised above its normal set point of 60°C, to 65°C. This implies that more thermal energy is stored in the storage tanks.

This method allowed the load to be shed completely between 18:00-20:00, which are the two most expensive RTP hours. The operational cost for this system was reduced to 7.75 c/kWh, which is a 27.7% cost reduction compared to the uncontrolled system. It is also a further 3.2% improvement on the system control used in the previous example.

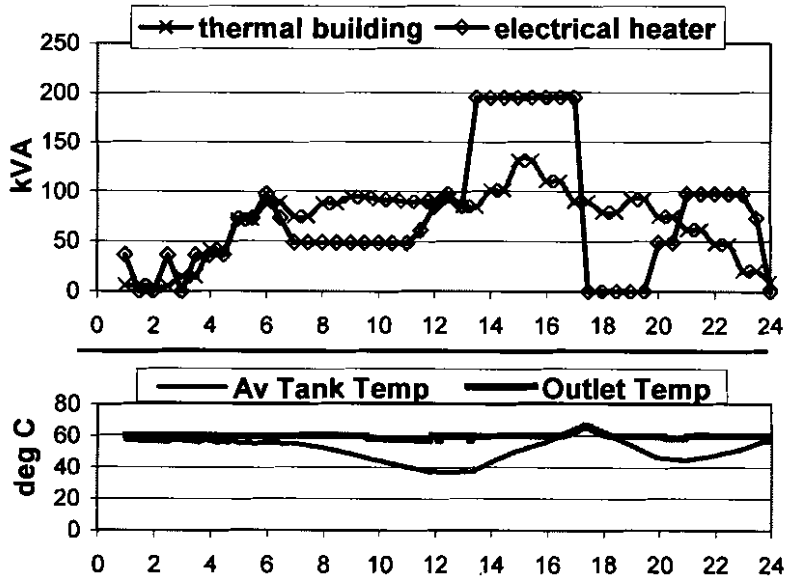


Figure 15: Example 1- DHS with intervention control & digital system switch-off control

7.2 Example 2: System with $V^*=0.3$ and $Q^*=1.8$

7.2.1 *System without digital control*

A system with a 120kW in-line heater and 9000-liter storage capacity is used in this example. The daily hot water consumption total and the consumption profile is the same as in Example 1. Due to the smaller non-dimensional heating capacity the system will have a much higher heating load factor compared to the system in Example 1. The slightly smaller storage capacity will also cause intervention to occur more often in peak hot water consumption periods. Figure 16 shows the simulated profiles for the system without digital control. The operational cost is 10.68 c/kWh, which compares well with the operational cost of the analogue control system in Example 1.

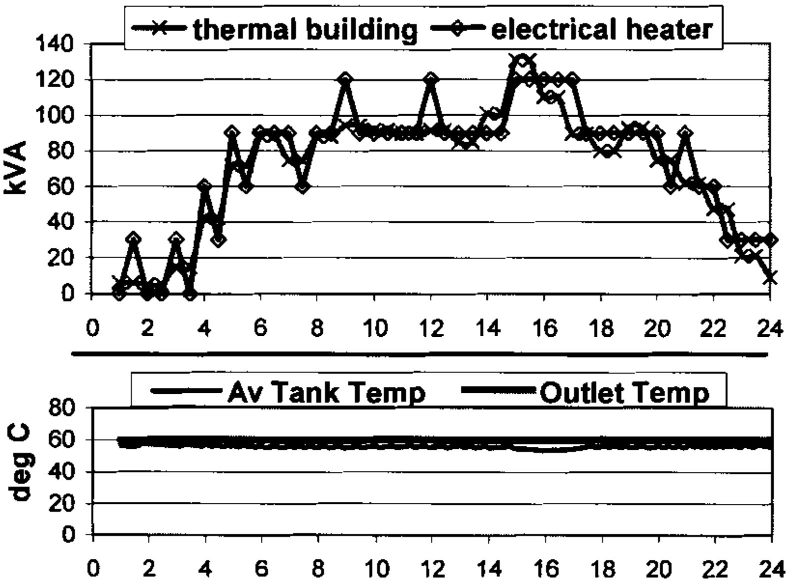


Figure 16: System without digital control

7.2.2 *System with digital control*

Figure 17 shows the simulated profiles for the same system, utilizing the digital control system that includes the DHS, intervention control and digital system switch-off control. It can be seen that the digital system switch-off control was activated but not fully utilized, since the storage tanks were never filled completely with hot water before the scheduled load-shedding period between 18:00-20:00. This leads to the load not being shed completely during the peak RTP price hours between 18:00-20:00. The operational cost is 8.21 c/kWh, which is slightly higher than Example 1, but still a 23.1% reduction in operational cost compared to the analogue control system in this example.

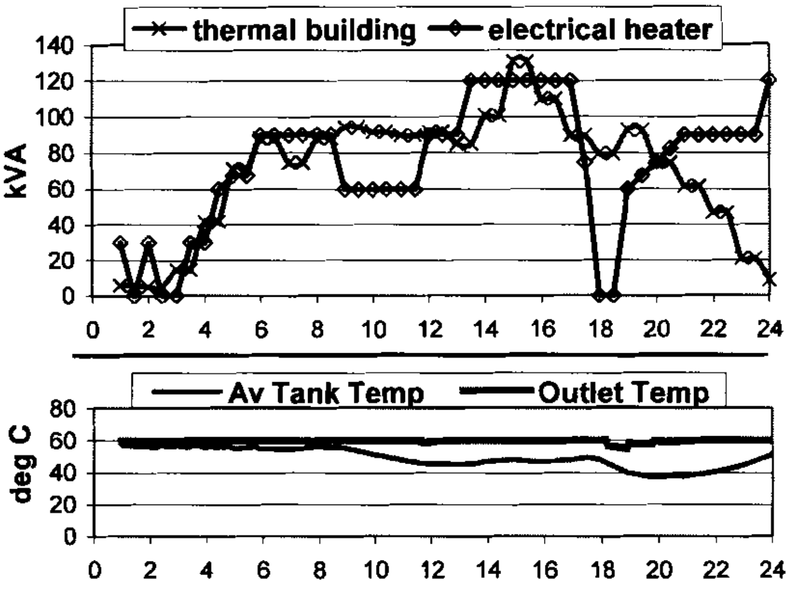


Figure 17: Example 2 – System with digital control

7.3 Example 3: System with $V^*=0.25$ and $Q^*=1.4$

7.3.1 System without digital control

A system with a 96kW in-line heater and 7500-liter storage capacity is used in this example. The daily hot water consumption total and the consumption profile is the same as in the previous examples. Figure 18 shows the simulated profile for the system without digital control. The operational cost is 10.74 c/kWh.

7.3.2 System with digital control

Figure 19 shows the resultant profiles for the same system, utilizing the digital control system. It can be seen that the digital system switch-off control was again activated between 15:00-18:00, but not fully utilized. The storage tanks were never filled completely with hot water before the total load-shedding period, which is similar to Example 2. This leads to the load not being shed completely during the peak RTP price hour between 18:00-19:00, and the full heating capacity is activated between 19:00-20:00 at a high cost. The resultant operational cost is 8.61 c/kWh, which is higher when compared to the previous examples, but still a 19.8% cost reduction compared to the analogue control system in this example.

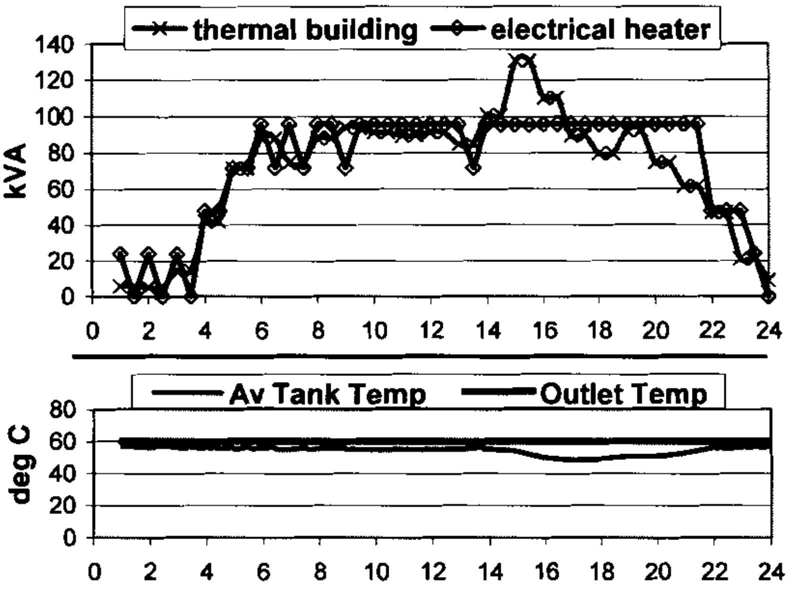


Figure 18: Example 3- System without digital control

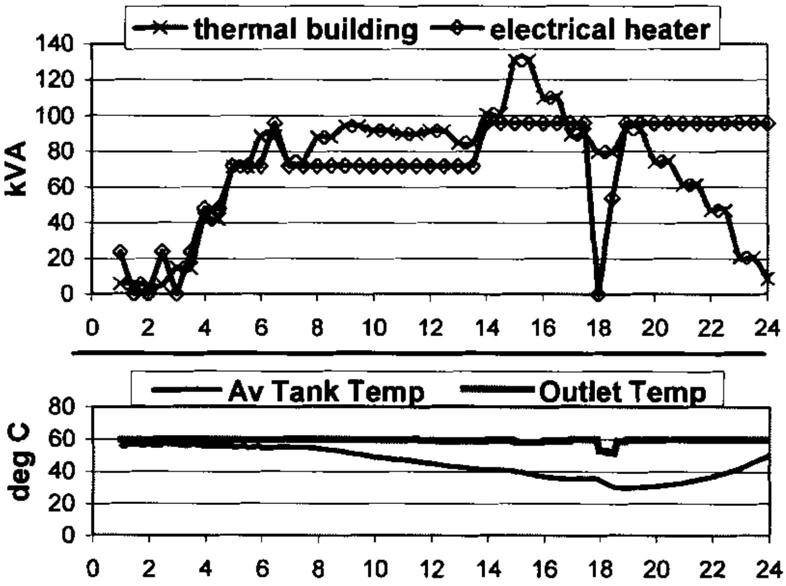


Figure 19: Example 3- System with digital control

8 Summary of results

From the results of the three case studies it can be seen that the non-dimensional heating- and storage capacity have an influence on the cost reduction capability of the system. Simulations are now done for a number of different non-dimensional heating and storage capacity combinations, to determine the influence of these parameters on cost reduction capability of the digital control model. These results are summarised in Figure 20.

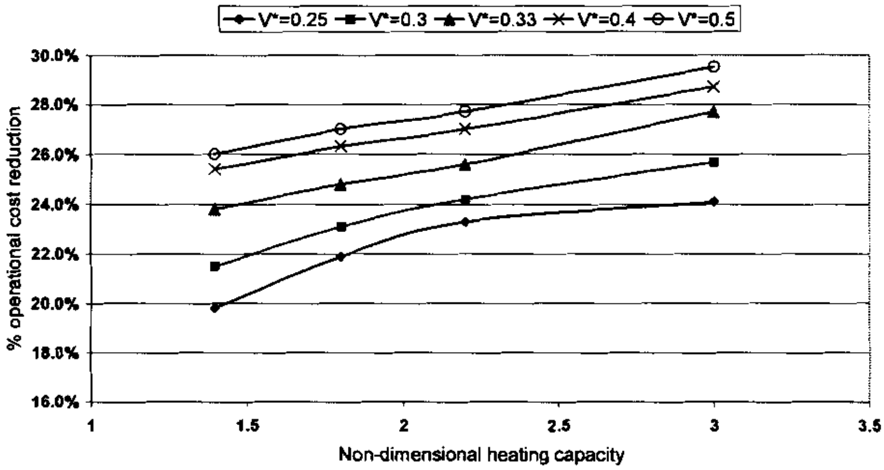


Figure 20: Summary of cost reduction for different combinations of heating and storage capacity

Both heating and storage capacity influence the cost reduction capability of a heating system. Maximum cost reductions are obtained with the biggest non-dimensional heating and storage capacities, and minimum cost reductions with the smallest non-dimensional heating and storage capacities. This trend can be explained as follows:

- A bigger storage capacity allows more heating to be done during low cost periods, thereby utilizing the price profile more efficiently. This in turn allows the heating load to be shed for longer periods when the energy cost is high, without consuming all the thermal energy in the storage facility.
- Larger storage tanks are however of no use if the heating capacity is not enough to provide sufficient hot water for storage in the tanks.

9 Economic impact extrapolated from results.

The potential economic impact of the digital control system can now be determined for actual systems. The Demand Side Management project described in Chapter 4 with 34 in-line heating systems is taken as an example. The specifications of all 34 in-line heater systems fall into the different combinations of heating and storage capacities as shown in Figure 20. The simulation results for these systems without digital control showed an average operational cost of 10.71 c/kWh of thermal energy consumed at the residences. An average cost of 8.04 c/kWh was obtained for the systems utilizing the digital control system developed in this chapter. This represents a difference of 2.67 c/kWh, which is a 24.9% average cost reduction.

In Chapter 2 it was shown that a yearly average of 81 litres of hot water at 60°C is consumed per person per day at the sanitary hot water facilities in the mine residences. With a total of 13000 mine residence occupants using these facilities, a total of 1053 kiloliters are consumed on average per day, and 384 000 kiloliters per year. With an average yearly inlet water temperature of 14.1°C, the total amount of thermal energy consumed is 20520 MWh per year. From this estimation, the mine that participated in this project can obtain an estimated saving of R548 000 per year on water heating system operational cost.

10 Conclusion

This chapter described the development of a digital control model for sanitary water heating systems subject to RTP. The model attempts to optimise the cost effectiveness of the system without compromising hot water availability. The development of a DHS was described that provides the optimal operational cost schedule for the water heating system. An Intervention Control algorithm was also developed that intervened in the heating schedule to avoid hot water deficiencies, by using measurements taken from the hot water storage facility. Additional control measures to optimise the cost effectiveness and hot water availability were also developed such as a) Master Override Control, preventing hot water run-out, and b) digital switch-off control, which attempts to boost thermal storage before critical load shedding periods.

The digital control model was tested with the simulation program developed in Chapter 5 of this thesis. Substantial cost reductions for a specific system were obtained by utilizing the DHS in conjunction with the Intervention Control and digital system switch-off control. Results showed that an operational cost reduction of typically 20%-29% is possible when the digital control system is used. Cost reduction potential is higher for bigger non-dimensional heating and storage capacities.

Simulation results based on the 34 in-line heater system installed at the AngloGold Ashanti mines showed a reduction in operational cost of 2.67c/kWh (R26.70/MWh) of thermal energy consumed by the water heating system users. This can lead to significant savings in operational costs for sanitary water heating systems subject to Real Time Pricing.

CHAPTER 8 - CLOSURE AND RECOMMENDATIONS FOR FURTHER WORK

1. Preamble

In Chapter 1 background was provided on the role of DSM in general in the South African energy industry. Focus was then shifted to the role that sanitary water heating systems can play in the DSM industry, and the need for this study was subsequently identified. A summary of the most important literature survey findings pertaining to this study was then provided. From this emanated the scope of work and the objectives of this study was clearly stated. Chapter 2 to Chapter 7 attempted to address the objectives of the study, with each chapter addressing an issue that can be viewed on its own, or as part of a broader picture. The broader picture is defined in the title of the thesis as follows:

"Optimization of the in-line sanitary water heating system for Demand Side Management in the South African commercial and industrial sectors"

The outcome of this study should now be evaluated in terms of the objectives as laid out in Chapter 1, and ultimately in terms of the title of this thesis as provided above.

2. Evaluation of the study; have the objectives been reached?

Chapter 2

In Chapter 2 new hot water consumption patterns were provided for hotels and mine residences. The differences between these profiles, and those found in previous studies for the residential sector were highlighted. This was achieved by a simulation study, which resulted in a design envelope for the most important system specifications for different hot water consumption profiles.

A possible shortcoming of this study is that only hotels were evaluated of all the building types in the commercial building sector. The study therefore does not address the commercial sector as a whole, as laid out in the title of the thesis. Another important building type in the commercial building sector utilizing sanitary water heating systems is hospitals. The main difference between hospitals and hotels is however the interest shown by building owners for cost efficiency upgrades. Due to the economically competitive nature of the hotel industry, hotel owners are generally more interested in increasing their cost efficiency, compared to the partially state funded hospital industry. The conclusion can therefore be drawn that at this stage, hotels are the most viable commercial building type for DSM programs. This might however change in the near future as more hospitals become privatised, and the study should be expanded to include measuring hot water consumption patterns in hospitals. Further building types in the commercial sector that should also merit study are university residences, prisons and military institutions.

Chapter 3

This chapter provided results from a research and implementation project completed at several hotels, where in-line heat pump sanitary water heating systems were installed and monitored. Results showed that such installations could provide reductions in building peak demand, which benefits both utility and building owner. Additional benefit for the building owner is obtained by the improved energy efficiency of the system due to the installation of a heat pump unit. Favorable payback periods mean that these projects can potentially be rolled out with building owner funding, instead of requiring utility DSM funding.

Chapter 4

This Chapter provided results from a large scale DSM implementation project completed at Anglo Gold Ashanti mines in South Africa. 34 in-line heater installations were completed, and a summary of results was given by providing three examples, and the total DSM potential achieved by the project. This chapter focused on the DSM benefits achieved by the utility only. The client obtained only indirect benefits from this implementation in terms of load being shifted out of a period that typically is an expensive price period on the Real Time Pricing tariff. To obtain additional benefits for the client the newly installed systems can be configured to optimise the cost efficiency of the system based on the forecasted RTP prices. This is however addressed separately in Chapter 7.

Chapter 5

The simulation model developed in this chapter successfully demonstrated a high level of accuracy for both electrical demand and thermal availability prediction of sanitary water heating systems. The simulation program can therefore be used with confidence, should the engineer or system designer intend to use the program within its stated constraints.

An advantage of this model is its simplicity. The model only requires an explicit solution to its equations. This means however that large time steps will provide a level of inaccuracy, since data from the previous time step is used in the explicit solution. For this reason small time steps have been used in the simulation program. Its simplicity allows easy upgrading to include more heating algorithms. This is illustrated in Chapter 6 and Chapter 7 of this thesis.

Chapter 6

The simulation program developed in Chapter 5, together with the hot water consumption patterns for hotels determined in Chapter 2, were used in this optimization study for commercial building water heating systems. The study provided optimal heating and storage capacities for a broad range of system specifications. This is required when an existing system with a fixed storage capacity is retrofitted. The most optimal heating and storage capacity when designing a completely new water heating system was also provided. The study also showed that additional control upgrades provided better economic returns from the system.

Care was taken not to overcomplicate the design of such a water heating system. The design and control algorithms for this system is however more complex than a simple thermostatic controlled water heating system. Projects that have already been completed on this type of system retrofit have however allowed accurate cost estimates of these retrofit proposals. This allowed a full economic evaluation of all optimisation proposals. This in turn led to some of the evaluated proposal not proving to be economically viable for the 'time-of-use' type tariff in the commercial building sector.

In summary it can however be concluded that although the system is more complex and expensive to implement when compared to conventional heating systems, the economic viability of the proposed design guidelines is very high, with favourable payback periods for the building owner.

The optimized system also proves beneficial to ESKOM as a DSM option, if the building utilises a tariff that includes a maximum demand charge. The same can however not be concluded for buildings utilizing the 'time-of-use' tariff found in the commercial sector. The penalty involved in having a high demand for short periods in peak demand times is not enough to discourage clients to completely reduce electrical demand.

Chapter 7

The digital control model developed in this chapter showed that significant savings can be achieved in the industrial sector for sanitary water heating systems subject to Real Time Pricing. This improvement in cost efficiency can be obtained without a loss in hot water availability. The model is based on a simplified approach towards predicting system operation. The simplicity of the model will allow it to be programmed onto a PLC controller, thereby reducing implementation cost and improving reliability, when compared to a computer controlled system.

The study showed however that savings are dependant on system specifications. A system with an oversized heating and storage capacity provides higher savings potential, while a system with smaller heating and storage capacity has a lower savings potential. The worst-case scenario is a system that operates on full installed capacity for 24 hours per day. No savings potential exist for such a system, since no load shifting can be achieved.

The above observation highlights one of the major differences between industrial and commercial sanitary water heating system design. In the commercial sector the primary heaters are designed as small as possible to allow a maximized runtime. This allows the best peak demand reduction option for the building owner. In the industrial sector however the most desirable option is to have the biggest possible heating capacity. This allows more flexibility in terms of load shifting. This again emphasizes the importance of taking into account the type of electrical tariff utilized when a water heating system is designed.

A shortcoming identified for this study is the fact that the digital control model has not been tested in real practice. For this reason no cost of implementation could be associated with the control model, thereby allowing no evaluation on economic returns. Savings were only presented in terms of simulated operational cost reductions, and not in terms of internal rate of return. The testing of this digital control model on actual water heating systems should therefore be a recommendation for further work.

3. Recommendations for further work

The previous section evaluated whether the study achieved the objectives as laid out in Chapter 1. The shortcomings found are summarised here as recommendations for further work.

- Hot water consumption patterns should be determined for other buildings in the commercial building sector, such as hospitals, university residences, prisons and military institutions.
- The optimized guidelines for commercial sector systems should be re-evaluated when new hot water consumption patterns are obtained for buildings such as hospitals. As shown in Chapter 2, different hot water consumption patterns in different building types can have an influence on system design, and its impact on the optimized design guidelines should therefore be evaluated.
- The actual implementation of the digital control model developed in Chapter 7 should be tested on real world in-line water heating systems. A study of the economic viability of the implemented digital control system should then be done.

4. Closure

Finally it can be concluded that the study achieves its main objectives as set out in the title of this thesis. Chapter 2 to Chapter 5 provided a foundation from which the methods developed in Chapter 6 and Chapter 7 were evaluated. Chapter 6 provided optimized design guidelines for commercial sector systems, and a digital control model for optimized control in the industrial sector was provided in Chapter 7. These studies provide 'real world' solutions with a well balanced trade-off between simplicity and efficiency. Well-evaluated options for DSM programs in the different sectors are therefore provided, which can obtain benefits for both electrical utility and client. These options should therefore be able to boost the viability of sanitary water heating system related DSM projects in the Energy Services Industry.

APPENDIX A

DEFINITIONS OF NON DIMENSIONAL PARAMETERS

- Non-dimensional temperature is defined as follows:

$$T^{*}=\frac{T_{actual}-T_{inlet}}{T_{set,\,out}-T_{inlet}} \qquad \textbf{Eq 1}$$

with T_{actual} the actual measured outlet temperature, and $T_{set,out}$ the set-point outlet temperature of the system. T_{inlet} is given a fixed value. This value is typically the minimum expected inlet temperature for the system (12°C in Chapter 6 calculations).

Non-dimensional set-point temperature is defined as follows:

$$T^{*}_{set}=\frac{T_{thermostat}-T_{inlet}}{T_{set,\,out}-T_{inlet}} \qquad \textbf{Eq 2}$$

with $T_{thermostat}$ the temperature set-point of a thermostat.

- Non-dimensional heating capacity is defined as follows:

$$Q^{*}=\frac{Q}{\rho\cdot V_{day}\cdot c_{P}\cdot\Delta T/(24\cdot 3600)} \qquad \textbf{Eq 3}$$

with Q the installed heating capacity, ΔT the maximum temperature difference between the hot water system inlet and supply, and V_{day} the maximum amount of hot water consumed daily.

- Non-dimensional storage capacity is defined as follows:

$$V^{*}=\frac{V}{V_{day}} \qquad \textbf{Eq 4}$$

with V the installed storage capacity of the system.

- Non-dimensional height in the storage tank is defined as follows

$$h^{*}=\frac{H}{H_{tank}} \qquad \textbf{Eq 5}$$

with H the height in question, i.e. where a thermostats needs to be installed, and H_{tank} the total height of the tank. In the case of multiple tanks connected in series, H_{tank} is the sum of the tank heights. H

will in this case be calculated as the height on the specific tank plus total tank heights of any tanks connected before this tank in the series connection.

- Internal rate of return (IRR) describes the return on investment obtained from investing in the project. A higher IRR will indicate a better economic potential for the project.

  IRR is determined by the following equation:

  $$C = S \times \left[\frac{(1+i)^n - 1}{i \cdot (1+i)^n} \right] \quad \textbf{Eq 6}$$

  C and *S* representing overhead costs and annual savings respectively, and *I* is the resultant the IRR. The completed project's lifespan is represented as *n* years.

APPENDIX B

OPTIMIZED GUIDELINES FOR COMMERCIAL BUILDING SANITARY WATER HEATING SYSTEMS

Chapter 6 evaluated several optimization proposals for the in-line heat pump sanitary hot water heating system. The resultant specifications were then tested by varying the most significant input parameters between set standard deviations. Slight changes were subsequently made to keep design parameters within the design constraints. The result obtained from this is an optimized guideline for commercial building sanitary water heating systems. Different guidelines are provided for the two different tariff structures found in this sector. Non-dimensional parameters were used meaning that these results can be applied to different size systems in hotels, depending on the type of tariff charged. Please refer to Appendix A for definitions of all non-dimensional terms used.

1 Guidelines for Tariff 1: Maximum Demand and Energy consumption flat rate

This sub-section provides the optimised guideline for Tariff 1 systems, where it is important to minimize maximum demand without compromising hot water supply.

Primary heater capacity (New system): $Q^* = 0.84$

Storage capacity (New system): $V^* = 0.67$

Primary heating capacity for existing systems with a fixed storage capacity.:

Figure 1 allows the system designer to choose the optimal heating capacity for a wide range of storage capacity values. The optimal choice for a specified storage capacity is the heating capacity providing the highest IRR.

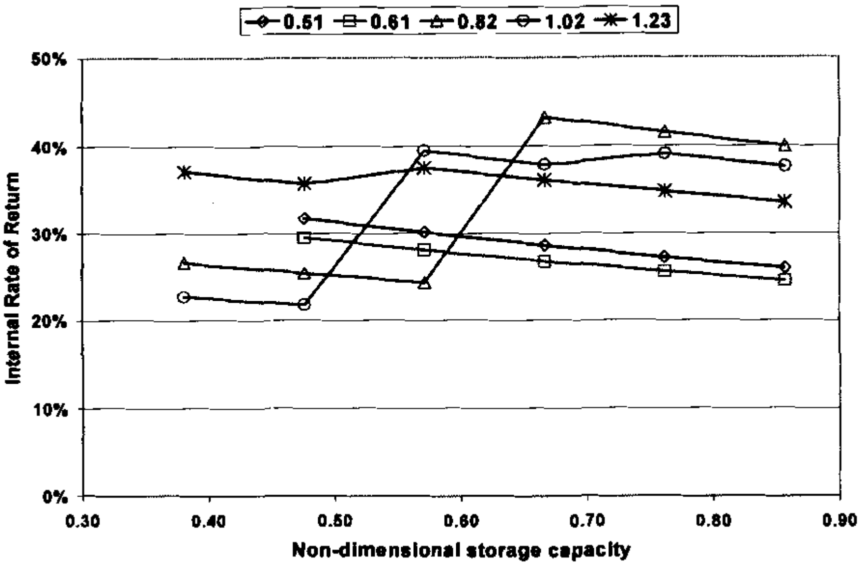


Figure 1: Choosing the optimal heating capacity for different storage capacity values, based on IRR.

Back-up heater capacity:

Stage 1 (Replace heat pump during fault signal, off-peak heating): $Q^* = 0.75$

Stage 2 (Assisting with heat recovery, off-peak heating): $Q^* = 0.5$

Stage 3 (Off-peak heating only) $Q^* = 0.5$

Combined heater capacity: $Q^* = 1.75$

Thermostat set points and positioning:

Heat pump & off-peak timer check thermostat (Bottom)	$h^*=0.0$,	$T^*=0.88$
Stage 2 Back-up heater	$h^*=0.6$,	$T^*=0.62$
Off-peak timer check thermostat (Top)	$h^*=0.3$,	$T^*=0.56$

System temperature supply set point ($T^*=1$) T=60°C

Heater configuration: (See Figure 2)

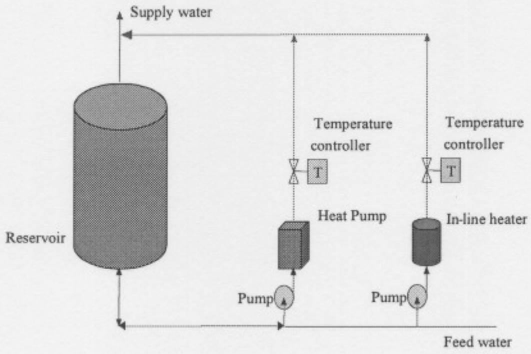


Figure 2: Improved in-line heat pump water heating configuration

Control algorithm: The control algorithm is provided in two formats:

1. A diagram that provides a logic description of the control algorithm is shown in Figure 3.
2. An IEC standard ladder diagram (Rullán (1997)) provides a layout of the control algorithm, showing the required electrical control equipment to achieve this control. This ladder diagram is shown in Figure 4.

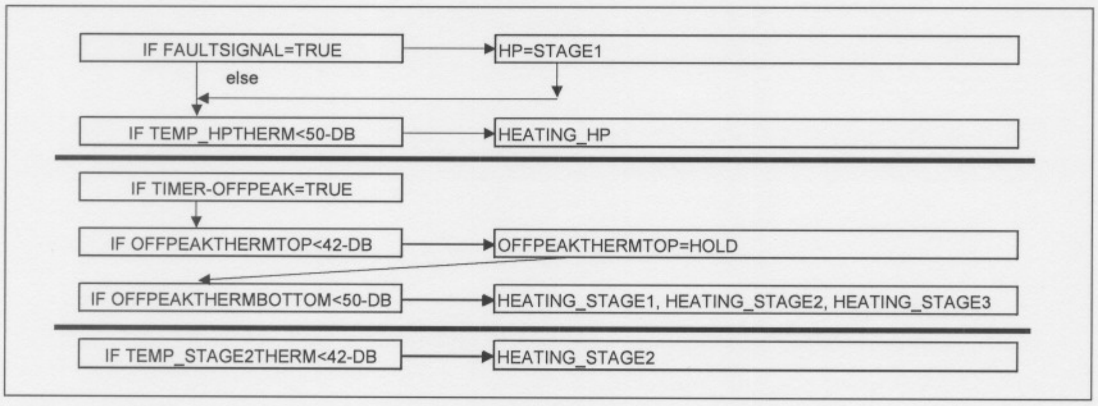


Figure 3: Control algorithm for Tariff 1 heating system

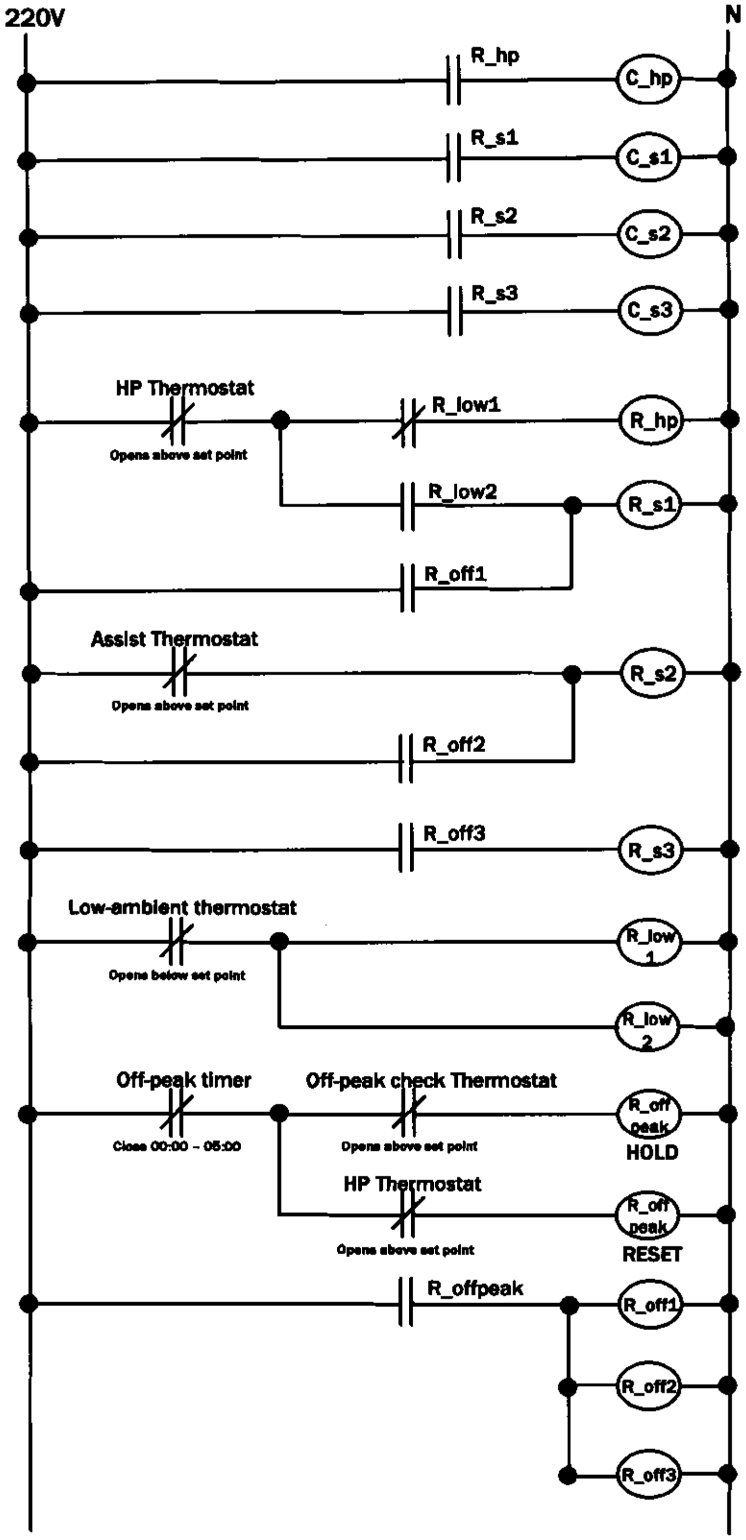


Figure 4: Ladder diagram for Tariff 1 control

2 Guideline for Tariff 2: Two-part time-of-use energy cost without Maximum Demand charge

This section provides the optimum guideline for Tariff 2 systems.

Primary heater capacity (New system): $Q^* = 0.51$

Storage capacity (New system): $V^* = 0.72$

Primary heating capacity for existing systems with a fixed storage capacity.:

Figure 5 allows the system designer to choose the optimal heating capacity for a wide range of storage capacity values. The optimal choice for a specified storage capacity is the heating capacity providing the highest IRR.

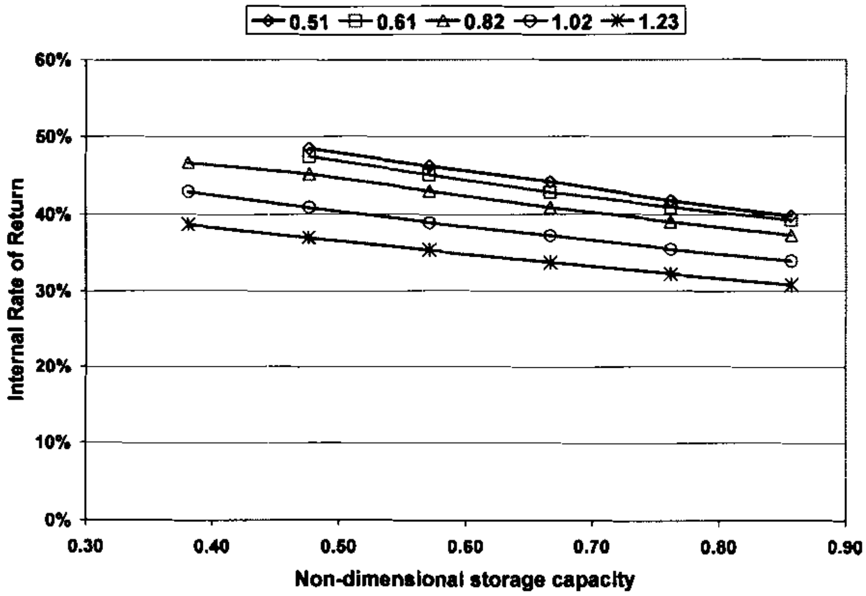


Figure 5: Choosing the optimal heating capacity for different storage capacity values, based on IRR.

Back-up heater capacity: $Q^* = 1.52$

Thermostat set points:

Heat pump thermostat & Off-peak timer check thermostat (Bottom) $h^*=0.0$, $T^*=0.88$

Back-up heater $h^*=0.6$, $T^*=0.62$

Off-peak timer check thermostat (Top) $h^*=0.3$, $T^*=0.56$

System temperature supply set point (T*=1.0) T=60°C

Heater configuration: (See Figure 2)

Control algorithm:

The control algorithm is provided in two formats:

1. A diagram provides a logic description of the control algorithm, shown in Figure 6.
2. An IEC standard ladder diagram provides a layout of the control algorithm, showing the required electrical equipment to achieve the desired control. This ladder diagram is shown in Figure 7.

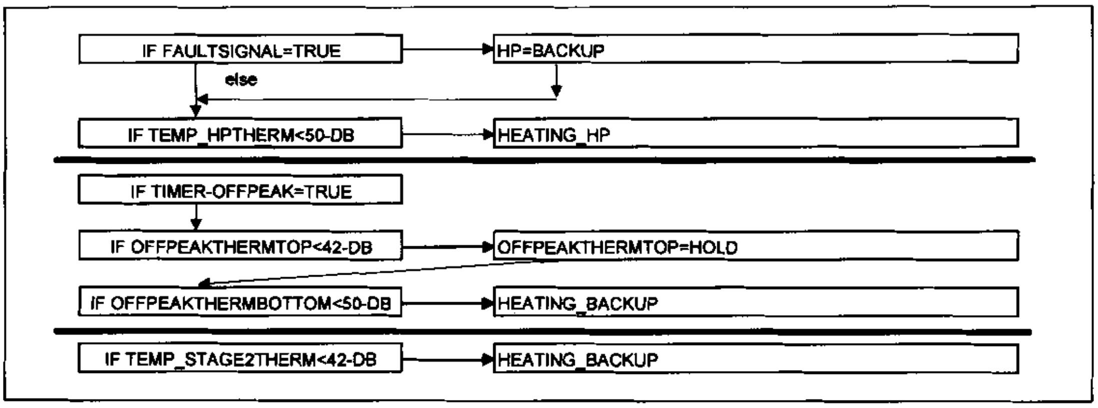


Figure 6: Control algorithm for Tariff 2 heating system

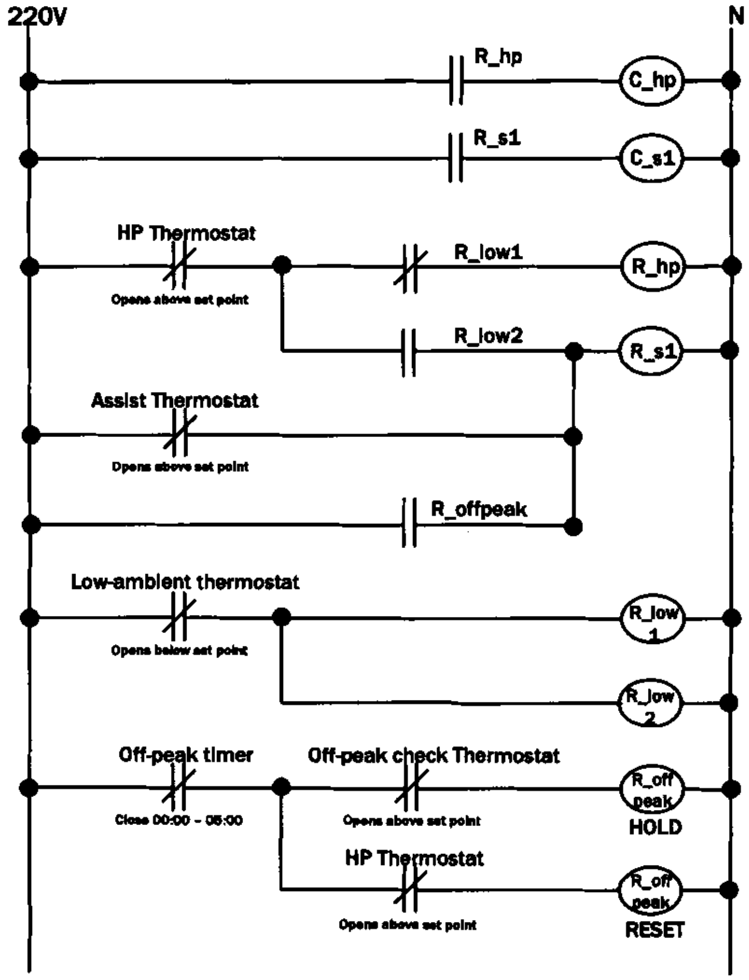


Figure 7: Ladder diagram for Tariff 2 control

APPENDIX C

UNCERTAINTIES ASSOCIATED WITH THERMAL AND ELECTRICAL MEASUREMENTS AND CALCULATIONS USED IN THE EVALUATION OF SANITARY WATER HEATING SYSTEMS

In chapter 3 and chapter 4 of the thesis, data is presented from actual heat pump and in-line heater installations. Measurement equipment used to collect the data included electrical power meters, temperature sensors and water flow meters. This appendix provides the standard uncertainty contribution of each measuring instrument. The combined standard uncertainty of the parameters that is calculated with the direct measurements is then provided. All terms and equations used in the appendix are based on the guide to the expression of uncertainty in measurement as provided by the International Standards Organisation (1993).

1 Specified measurands

1.1 Electrical measurements

All electrical data, including energy consumption and peak demand is measured and logged by an 'ION 7300 Power Measurement Logger'.

1.2 Temperature measurements

All temperature measurements are performed using Resistance Temperature Detectors (RTD's). IPMVP (2002) recommends the use of three or four wire type RTD's, since the use of two wire RTD's requires field calibration to compensate for varying lead lengths in application. All the measured plants make use of 3-wire RTD sensors, manufactured by Pyrotec Industries (Pty) Ltd.

1.3 Water consumption measurement

Water consumption measurement is performed at each plant by a turbine flow meter manufactured by Invensys®.

2 Specified parameters

2.1 Thermal energy

Thermal energy is calculated as follows:

$$Q = V \cdot \rho \cdot c_p \cdot (T_{inlet,av} - T_{outlet,av}) \qquad \textbf{Eq 1}$$

with V the total amount of hot water consumed during the time step and $T_{inlet,av}$ and $T_{outlet,av}$ the measured inlet and outlet temperatures, calculated as the average values for the time step.

2.2 Coefficient of Performance

Coefficient of performance of the water heating system is calculated as:

$$COP = \frac{Q}{E} \qquad \textbf{Eq 2}$$

with Q the total amount of thermal energy consumed by the building occupants, and E the total amount of electrical energy consumed by the water heating system.

3 Identify and quantify uncertainty sources

3.1 Instrumentation effects

Table 1 provides the uncertainty components of each measuring instrument, determined as function of the manufacturer specified maximum errors associated with each instrument.

Table 1: Specified standard uncertainties (Expressed in %)

Instrument	**Product code**	**Standard Uncertainty (%)**
Temperature sensors	Pyrotec Industries RTD-PT100 Model RTXL	**±0.25%**
Flow meter	Invensys® WPD0050 Turbine Flow meter	**±1.25%**
Power measurement	ION 7300 PML + CT's ANSI C12.16 accuracy compliant IEC 60687 acc class 0.5S compliant	**±0.5%**

3.1.1 Temperature difference

Temperature difference is calculated as follows:

$$\Delta T = T_{outlet} - T_{inlet} \qquad \textbf{Eq 3}$$

Typical values for T_{inlet} is 15°C and for T_{outlet} is 60°C, which results in a ΔT of 45°C. The uncertainty associated with temperature difference is therefore calculated using rule-1 for the sum or difference of quantities (ISO (1993)).

$$u_c(\Delta T) = \sqrt{u(T_{inlet})^2 + u(T_{outlet})^2} \qquad \textbf{Eq 4}$$

Since u(T)=0.25%, it follows that u(T_{inlet})=0.0375°C and u(T_{outlet})=0.15°C and therefore $u_c(\Delta T)$= 0.155°C. For ΔT =45°C, it can also be expressed as $u_c(\Delta T)$=0.344%.

4 Combined standard deviations

The most important parameters to consider in all the measured and calculated results presented in Chapter 3 are electrical energy, thermal energy, and the associated savings (Energy efficiency improvement).

4.1 Electrical energy

The uncertainty associated with the measurements of electrical energy is simply the standard uncertainty of the power meter and current transformers (CT's). Therefore from Table 1, (u(E)/E)=0.5%.

4.2 Thermal energy

Thermal energy is calculated (Eq 1) as a product of water consumption, density, specific heat and temperature difference. With specific heat and density fixed, it follows from rule-2 for products of quantities (ISO (1993)):

$$\frac{u_c(Q)}{Q} = \sqrt{(\frac{u(V)}{V})^2 + (\frac{u(\Delta T)}{\Delta T})^2} \qquad \textbf{Eq 5}$$

From (u(V)/V)=1.25% and (u(ΔT)/ΔT)=0.344%, it follows that (u_c(Q)/Q)=1.3%.

4.3 Coefficient of performance

COP is calculated (Eq 2) as a function of thermal energy and electrical energy. The uncertainty is therefore a function of both u(Q) and u(E), and is calculated as follows:

$$\frac{u_c(COP)}{COP} = \sqrt{(\frac{u(Q)}{Q})^2 + (\frac{u(E)}{E})^2} \qquad \text{Eq 6}$$

With (u(Q)/Q)=1.3% and (u(E)/E)=0.5%, it follows that (u_c(COP)/COP)=1.39%.

4.4 Energy efficiency improvement

An improvement in energy efficiency is obtained when the COP of the system is increased. The energy efficiency improvement is usually expressed as the difference between the electrical energy consumed before and after the retrofit. For the same amount of thermal energy, i.e. after the retrofit, the difference in electrical energy consumed would be related to the difference in COP. The amount of electrical energy that is actually saved by the new system is therefore calculated as follows:

$$\begin{aligned} S_{electrical} &= E_{Calc,old-COP} - E_{new} \\ E_{Calc,old-COP} &= \frac{Q_{new}}{COP_{old}} \end{aligned} \qquad \text{Eq 7}$$

with $S_{electrical}$ the electrical energy saved and (Q_{new}, E_{new}) the values for thermal and electrical energy consumed by the building and hot water system after the retrofit.

From this equation, the uncertainty of the savings can be estimated by using a combination of rule-1 and rule-2:

$$\begin{aligned} u_c(S) &= \sqrt{u_c(E_{Calc,old-COP})^2 + u_c(E_{new})^2} \\ \frac{u_c(E_{Calc,old-COP})}{E_{Calc,old-COP}} &= \sqrt{(\frac{u(Q)}{Q})^2 + (\frac{u(COP)}{COP})^2} \end{aligned} \qquad \text{Eq 8}$$

For (u(Q)/Q)=1.3% and (u_c(COP)/COP)=1.39%, it follows that (u(E_{Calc})/ E_{Calc})=1.9%.

Since (u(E_{Calc})/E_{Calc}) =1.9%, it follows that for Case 1 in Chapter 3 (See Table 3, Chapter 3), u(E_{Calc}) =1018kWh. With (u(E)/E) =0.5%, the uncertainty in the directly measured energy consumption after the retrofit is u(E) =77kWh. Using Eq 10 results in u_c(S) =1022kWh, or 2.67% of the energy consumption reduction.

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