

# **CHAPTER 1. INTRODUCTION**

## **1.1 The South African electrical energy demand**

There are increasing global concerns regarding the management and sustainability of energy resources (Abdelaziz et al. 2011). The management of electrical energy forms an important part of these concerns. Increasing electricity demands need to be suitably managed while taking into account the associated environmental, economic and sustainability factors. Sustainable energy systems are therefore priorities in various policies of many countries (Dong et al. 2013).

The worldwide demand for electrical energy is growing rapidly, with an increase of 33% being projected between 2010 and 2030 (Abdelaziz et al. 2011). This is also true for South Africa, where 43% of the total electricity consumed in Africa is used (Odhiambo 2009). The rapid increase in economic growth, industrial output and power distribution to previously disadvantaged communities has led to a large increase in South African electricity consumption since 1993 (Inglesi-Lotz and Blignaut 2011). In this regard, an increase of 59% in the national electricity demand between 1990 and 2020 was predicted (US Department of Energy 2005).

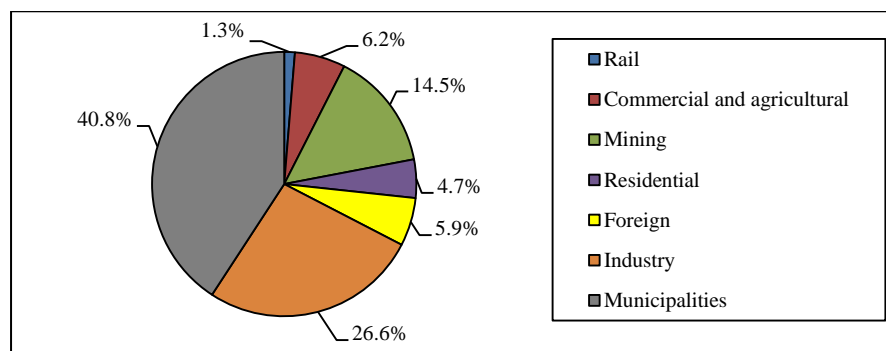
It is to be expected that a constant electricity demand growth will result in the demand eventually matching the available supply capacity, especially when supply capacities are not adequately managed (Calitz 2006). The relatively low historic electricity price in South Africa has added further pressure on the supply capacity problem (Kleingeld et al. 2009). In 2007 these factors led to the supply not matching the demand. The problem was temporarily resolved by load shedding, a system that interrupts the power supply to certain areas during specific times (Schutte 2007).

Eskom is the main electricity supply utility of South Africa and generates about 95% of the electricity used in the country. The maximum self-generated capacity of the utility is presently 41 194 MW (Eskom 2012). The majority of this electricity is generated by burning coal, making South Africa the seventh largest emitter of greenhouse gas (GHG) emissions per capita in the world (Sebitosi and Pillay 2008). Eskom manages both the supply and demand of electricity in order to address the rising energy demands in South Africa.

A capacity expansion programme is underway that aims to increase the national generated electricity capacity by 17 120 MW by 2018 to manage the supply. Although the national energy demand growth rate has recovered slightly from 2007 rates, the margin between supply and demand remains very slim. This is expected to continue until at least 2018 when the new power stations are to be completed (Eskom 2012).

The International Energy Agency (IEA) has shown that demand-side management (DSM) is more cost-effective than conventional supply-side policies (Perfumo et al. 2012). Eskom has a DSM programme to reduce the national electricity demand and thereby postpone the predicted date when the electricity demand will reach the generated capacity (Beggs 2002). DSM also serves to reduce environmental effects as well as capacity and capital costs needed for supply management (Bennet 2001). Eskom uses independent firms, or Energy Services Companies (ESCOs), to implement DSM projects. Typical project incentives include energy-efficient measures, load management and negotiated interruptible supplies (South African Department of Minerals and Energy 2005). Electrical power savings of about 2 700 MW have been realised in this way in South Africa since 2005 (Eskom 2012).

Studies have shown that there is still significant scope for widespread energy efficiency improvements through DSM, specifically by focusing more closely on high-demand sectors (Inglesi-Lotz and Blignaut 2011). In a global context, the industrial and mining sectors use about 37% of the world's total delivered energy (Abdelaziz et al. 2011). Similarly, the South African industrial and mining sectors use 41.1% of the national delivered electricity, as shown in Figure 1. This makes it the largest combined electricity consumer in South Africa.



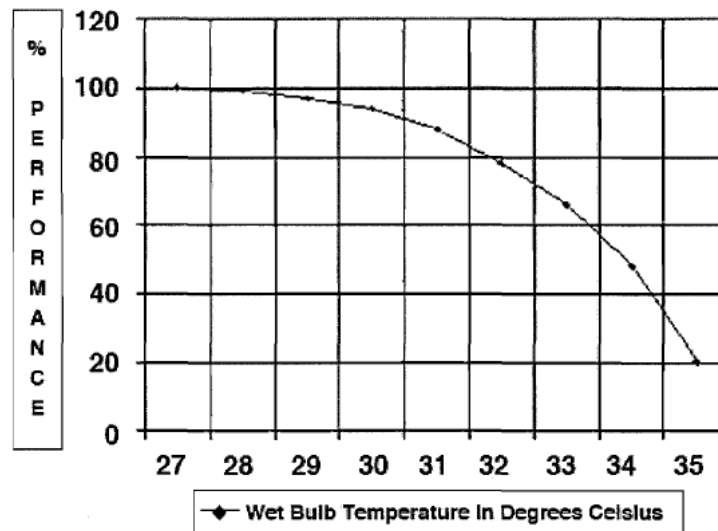
**Figure 1** Electricity sales in South Africa for 2011 (Eskom 2012)

Figure 1 also shows that the mining sector uses 14.5% of the total national electricity supply. This relatively large proportion is to be expected, since a large portion of the South African economy relies on mineral extraction and processing. It is important to note that the historically low electricity price has meant that there has been little incentive to save electricity in the mining sector in general (Schutte 2007). However, rising electricity tariffs and increasing pressure to manage energy are leading mines to reconsider their stance regarding energy saving initiatives in order to stay competitive.

It is reasonable to conclude that there is considerable potential to investigate, propose and implement new DSM initiatives specifically on South African mines (Hughes et al. 2006). Research in energy saving measures is promoted and advanced in the process, because the drive for such work is supported by mines as well as Eskom. Furthermore, energy saving interventions developed in this context can be applied elsewhere in similar industrial applications, leading to further reductions in national and international electrical energy demands.

## 1.2 DSM potential on mine cooling systems

Mines require acceptable environmental conditions for underground workers to enhance productivity. Figure 2 indicates the relation between workers' mental and physical performance and underground wet-bulb temperature to illustrate this (Le Roux 1990). It can be seen that when the underground wet-bulb temperature exceeds 32 °C, performance decreases significantly. This has clear implications on mine productivity as well as the health and safety of employees. For these reasons, the maximum underground wet-bulb air temperature in working areas is limited to 27.5 °C (Vosloo et al. 2012).

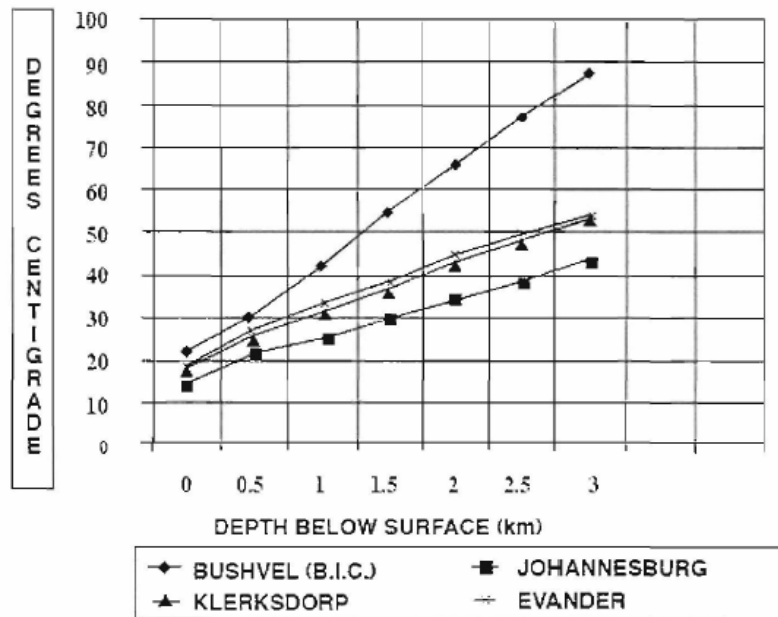


**Figure 2** Underground worker performance as a function of environmental conditions (Le Roux 1990)

Furthermore, underground mining equipment needs to operate efficiently. Therefore, sufficient cooling of water and ventilation air sent underground is required. Large cooling systems are thus found on most deep mines in South Africa. Mine cooling systems are integrated with water reticulation systems to supply chilled service water and maintain safe working conditions underground (McPherson 1993).

Figure 3 shows underground virgin rock temperature as a function of underground depth for various mining areas in South Africa (Nixon et al. 1992). It can be seen that as mining depths increase, so do the virgin rock temperatures.

It follows that the cooling demands, and hence the associated technical challenges also increase (Swart 2003). Beyond about 1 600 m, air and water cooling systems become exceedingly large energy consumers and dominant operating cost factors (Haase 1994). Such conditions are found on South African mines, especially gold mines.



**Figure 3** Virgin underground rock temperatures (Nixon et al. 1992)

On deep level mines with depths of more than 1 600 m, integrated cooling systems typically consume up to 25% of the total electricity used (Schutte 2007). For some deep mines environmental control can account for as much as 40% of the electricity costs (Stroh 1992). The ultimate future of deep level mining will therefore increasingly depend on the industry's ability to contend, in an acceptable and cost-effective manner, with the environmental control problems associated with the provision of satisfactory ventilation and cooling (Marx 1990).

Effective DSM largely depends on how well the specific initiative is suited to the particular type of industry. It has been shown that a popular general sector for DSM is cooling systems (Zehir and Bagriyanik 2012). Cooling and ventilation is a field that is generally energy intensive, but that also provides many potential areas in which energy usage can be optimised by efficient control. It is therefore a demand sector that promises strong returns in DSM and in which various load management efforts have been made (Grein and Pehnt 2011).

The need for new DSM initiatives on South African mines can be combined with the need for DSM methods on cooling systems. It follows that an investigation of a new DSM method on large mine cooling systems will be relevant within the larger context of energy research in South Africa.

Improving the energy and cost efficiency of mine cooling systems have been investigated by various studies. Pelzer et al. (2010) and Schutte (2007) developed a strategy that reduces and controls the inlet water temperature of chillers to improve the chiller coefficient of performance (COP). Swart (2003) and Van der Bijl (2007) considered the optimisation of electricity costs by developing load shifting strategies. These studies are all based on improved control and scheduling of existing infrastructure. There is still therefore the opportunity to develop new DSM methods with alternative approaches, such as energy efficiency improvement through new cost-effective technologies.

Most mine cooling systems have energy inefficient features, including oversized and old equipment, poorly maintained equipment, outdated control systems and inefficient control strategies. This makes them ideally suited to the identification and development of new DSM methods. More information about inefficient features of mine cooling systems will be given in Chapter 2.

Mine cooling systems present unique service delivery requirements. These include specified chilled water storage dam levels, chilled water temperatures and underground wet-bulb air temperatures (McPherson 1993). Mine productivity and safety standards depend on these constraints (Van der Walt and De Kock 1984). It is thus important that these constraints be adhered to when developing an energy saving strategy.

Energy saving measures developed for mine cooling demands can potentially be adapted to large cooling systems in energy intensive industries other than mining. This widens the potential for new DSM methods. It also emphasises the importance of using the shown potential and available opportunities presented on mine cooling systems for the development of new DSM measures.

It can be concluded that the large cooling systems of mines present viable DSM opportunities for the development of a new energy saving strategy. This is mainly because of the good energy management potential generally found in cooling systems, the increasing electricity costs associated with mine cooling, the lack of energy efficient strategies currently employed in mine cooling and energy inefficient operations found on mines at present. The successful and cost-effective implementation of a new DSM method for mine cooling systems might lead to its extension to other industries, supporting the current incentive for its development.

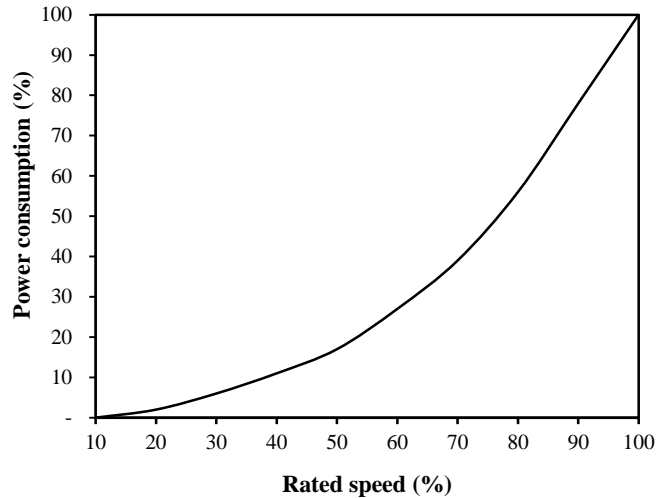
### **1.3 Energy management potential through variable water flow**

The South African government has pledged a greenhouse gas (GHG) emission reduction of 34% by 2020 (Winkler et al. 2010). One of the key national plans to achieve this, while avoiding reduced economic growth, is to improve industrial energy efficiency (Parliament of South Africa 2011). This further supports the potential specifically for new energy efficiency DSM measures on mine cooling systems, as opposed to load shifting or peak clipping methods. There are currently no energy efficiency DSM initiatives on mine cooling systems in South Africa.

Energy efficiency improvement through new technology is an important and usually significant DSM initiative in industrial systems (Xia and Zhang 2010, Abdelaziz et al. 2011). When investigating the potential focus of a new technology energy efficiency strategy for mine cooling systems, the most logical place to start is to consider the state-of-the-art of cooling systems in other industries.

Studies have shown that using variable speed drives (VSDs) to control electric motors is one of the most efficient and promising methods of utilising partial load conditions to realise energy savings (Mecrow and Jack 2008). For example, the increased frictional resistance and pressure drop as a result of valve control can be eliminated or significantly reduced when opening the valve fully and modulating the flow by VSD control instead. Using VSDs in variable torque applications such as pumps, fans and chiller compressors is of particular significance. Large energy savings can be obtained for relatively small variations in motor speed and fluid flow, as explained by the theoretical cubic power-flow affinity law and shown in Figure 4 (Saidur et al. 2010).





**Figure 4** Electric motor power consumption as a function of speed (Saidur et al. 2010)

Variable speed technology has therefore long been considered a standard energy efficient method to enhance the energy performance of chiller systems (Yu and Chan 2010). This is particularly true when the potential exists to control the chilled water supply to accurately meet the system demand. In typical residential and commercial applications flow control has been utilised in various ways. This includes the use of VSDs on cooling compressors to optimise operating speed at part-load conditions (Apprea et al. 2009, Romero et al. 2011). This also applies to load-based speed control of cooling tower fans, evaporator and condenser water pumps (Yu and Chan 2010, Lee et al. 2012).

Mine cooling systems generally show good potential for the control of chilled water to accurately match user demands. Hot and chilled water dams are typically found in these systems to provide storage capacity (McPherson 1993). This ensures that peak water demands can be met while, simultaneously, catering for the fluctuation in water flow requirements. It is common for the actual demand flow rates to be lower than the designed supply flow rates, resulting in continuous recycling of the chilled water from the chilled water dam to chiller inlets. It is also common practice to use variable opening control valves for water flow control. Furthermore, part-load conditions are presented by daily ambient condition fluctuations and the intermittent nature of water usage underground.

VSDs are not commonly found on mine cooling systems, even though these systems indicate good general potential for variable-flow methods. The lack of VSD acceptance can be attributed to a general lack of awareness and initiative. It is believed that this is due to the historically low electricity tariffs in South Africa. Energy efficiency was not a priority on mines until the late 1990s, leading to most personnel not actively pursuing energy saving measures.

The development of a novel mine cooling system energy saving strategy based on existing variable water flow methods and technologies therefore shows great potential. However, the successful application of variable water flow depends on how the water flow and chiller capacity can be adjusted to match changing load conditions (Bahnfleth and Peyer 2004). It is therefore important that the new strategy is specifically developed taking the unique mine cooling, as well as operational and safety requirements, into account.

A central energy management system that is developed specifically for mine cooling systems will ensure that a new energy efficiency strategy considers unique mine cooling demands. It will ensure that the DSM initiative is implemented effectively on the integrated cooling system.

Building energy management systems (BEMS) have gained popularity in contributing to continuous energy management of active building systems such as heating, ventilation and air-conditioning (HVAC) systems (Doukas et al. 2007). Considerable research efforts have been made in recent years to add advanced control methods to BEMS systems (Kanarachos and Geramanis 2008, Kolokotsa et al. 2010, Ma and Wang 2011). However, it has been shown that simple, integrated energy management methods that provide remote control and real-time energy consumption monitoring are still required (Bayindir et al. 2011). Such methods have been presented for building systems by Marinakis et al. (2013) and Doukas et al. (2007).

In industrial energy intensive systems, Lee et al. (2011) developed an energy management system to be used in conjunction with facility monitoring and control systems (FMCS). This system monitors and optimises HVAC and chiller energy consumption of industrial information technology (IT) plants. Vosloo et al. (2012) developed a method that simulates, optimises and controls the water reticulation network of a deep level mine.

Optimising control systems of mine ventilation systems have been investigated (McPherson et al. 1972, Meriluoto 1983, Hu et al. 2003). However, the majority of these systems do not simultaneously address the concerns of operational efficiency, control robustness and computational costs (Ma et al. 2008). Their complexity therefore generally leads to unreliable, impractical implementation.

It follows that the requirement for an integrated, generic energy management system for large mine cooling systems can be extended to one which is effective, yet sufficiently practical, robust and reliable. Such a central energy management system that not only controls specific subsystems according to energy efficient variable-flow strategies, but also monitors and manages the integrated system and its auxiliary equipment optimally, has not been developed for mine cooling systems.

It can be concluded that the proven need for a new DSM method for mine cooling systems can be further narrowed down to the need for improved energy efficiency. It has been shown that VSDs are not commonly found on mines, although VSD technology is a popular cost-effective feature of modern chiller systems. Typical part-load conditions and inefficient operational methods on mine cooling systems indicate that there should be potential to develop a variable water flow strategy to save energy on these systems. Furthermore, a central energy management system that is capable of integrating and implementing variable water flow strategies in a simple and practical way does not currently exist for mine cooling systems.

## **1.4 Need for this study**

From the preceding discussion it is clear that there is currently no study or published work that describes a new DSM energy efficiency initiative for large cooling systems based on variable water flow strategies. Furthermore, no integrated energy management system exists that can implement and integrate such strategies on large cooling systems like those found on mines. It is therefore apparent that a need exists to develop such a strategy and energy management system.

The overall need for this study is supported by the following summarised findings:

- Global electrical energy consumption is predicted to grow by 33% over the next 20 years. Industrial and mining sectors account for 37% of the world's energy usage. There is thus a general global need to improve the energy efficiency of industrial systems.
- In South Africa, the mining sector is energy intensive and uses 14.5% of the total national electricity supply. Mine systems are often found to be energy inefficient as a result of the historically low electricity tariffs in the country. It is thus sensible to continually develop new DSM methods specifically for mine systems.
- Large cooling systems are found on South African mines to maintain acceptable underground conditions for personnel and equipment. These systems can contribute up to 25% of total mine electricity usage.
- Cooling systems usually present potential for optimal energy management. No energy efficiency strategies are employed on large mine cooling systems in South Africa at present. It follows that there is potential for cost-effective DSM energy efficiency improvement, more specifically on large cooling systems such as those found on mines.
- It has been shown that the implementation of VSD technology realises large energy savings in cooling systems in general. However, there are no VSDs on South African mine cooling systems.

- Variable-flow strategies should be developed to enable the efficient control of VSDs on a specific type of cooling system. Various such examples exist, but no variable water flow strategies have been developed for large mine cooling systems.
- Mine cooling systems generally present viable potential for variable-flow methods to match chilled water supply with demand, instead of oversupplying the demand as most systems do at present.
- Many central energy management systems exist that implement energy saving strategies on specific integrated systems, but none that implement variable water flow strategies on large integrated cooling systems. It has been shown that the need for such an energy management tool involves the requirements of being cost-effective, simple, practical and robust and that it should be able to integrate, manage, monitor and report on the developed energy saving strategies.

The development of a new variable-flow energy efficiency strategy is shown to have immediate potential, particularly on large mine cooling systems. However, the successful development of a new DSM method for mine cooling systems might lead to its extension to other industries that use large cooling systems that are similar. This means that, although this study focuses more closely on mine cooling systems as an example of large cooling systems, the incentive for its development potentially stretches further.

## 1.5 Research hypothesis

A rational scientific research approach should involve the identification of a basic problem, the reduction of the problem to a set of more specialised and simpler problems, and the systematic solution of the simpler problems to arrive at a solution to the original basic problem (Maxwell 1985).

It has been shown that there is a need for new DSM initiatives on South African mines and industrial systems, that the large cooling systems of mines present viable DSM opportunities and that VSDs are not widely found on these systems even though there are indications of variable-flow potential through part-load conditions. The basic problem of this study can be formulated as the need to develop a variable water flow strategy that will realise energy savings in large cooling systems.

The research hypothesis can be stated as follows: **a variable water flow strategy will realise energy savings in large cooling systems without adversely affecting service delivery and system performance.**

The main research objective is to develop a new variable water flow strategy to realise energy savings in large cooling systems. This should then be experimentally validated to prove, or disprove, the hypothesis.

The main objective can be addressed systematically by reducing it to a series of objectives as follows:

The immediate focus area is mine cooling systems because they present significant general DSM potential. The study should begin with a preliminary investigation to estimate the large-scale VSD potential on mine cooling systems in South Africa. This must be done in the form of an energy audit on many mine cooling systems and preliminary calculations to estimate the saving potential. The results should indicate expected savings and indicate the most feasible application of VSDs on these systems.

Using the preliminary investigation results and findings from literature, a new variable water flow control strategy should be formulated that will allow energy savings to be realised from VSDs while adhering to mine cooling service delivery requirements and system performance limitations. This will typically involve strategies for subsystems such as evaporator, condenser, bulk air cooler and pre-cooling water pumps. A new energy management system that is practical, simple and robust should then be developed to integrate and implement the strategies in real-time on any large cooling system.

The feasibility of the developed variable-flow strategy and energy management system (collectively called the developed energy saving strategy) should then be evaluated by a study involving the use of a verified simulation model to predict energy savings and a techno-economic analysis to evaluate the economic viability. This will most easily be done specifically for a chosen primary case study site, namely the Kusasalethu cooling system.

After viability has been shown, the energy saving strategy should be implemented on the primary case study site and all relevant details regarding implementation, measurement and verification must be discussed. The *in situ* results of the energy savings as well as the various effects on service delivery and system performance must be evaluated for the primary case study as experimental validation of the proposed and developed energy saving strategy.

As a further validity investigation, the results of implementation on three other case study sites should be summarised and discussed. The potential to extend the strategy to non-mining large cooling systems should also be investigated through simulation.

Finally, all experimental findings should be summarised and conclusions formulated concerning the successful development of a new variable water flow strategy for energy savings in large cooling systems.

## **1.6 Contributions of this study**

The study addresses the presented need of a variable water flow strategy for energy savings in large cooling systems. There are various elements contained within the thesis that involve novel contributions to the knowledge fields of large mine cooling systems and DSM methods. A summary of these contributions is given below.

### **VSD potential study on South African mines**

Making it the most comprehensive audit to date on the largest number of mine cooling systems, a preliminary investigative energy audit was done on 20 South African mine cooling systems to determine the large-scale potential for VSDs on these systems. Currently, there are no VSDs implemented on any of these cooling systems. The findings of this investigation are novel in the sense that for the first time the potential for energy savings through VSD technology on mine cooling systems has been put into perspective. It significantly increases the industrial awareness of the potential benefits involved.

### **Variable water flow DSM strategy**

A new variable water flow strategy that describes simple control methods for evaporator, condenser, BAC and pre-cooling water flow was developed specifically for large mine cooling systems. Potential to expand it to non-mining industrial cooling systems was also shown. Variable-flow methods have been used on heating, ventilation and air-conditioning systems. However, no such methods have previously been proposed, developed, implemented or analysed experimentally for large cooling systems found on South African mines.

### **Central energy management system**

A novel energy management system that integrates, controls, monitors and reports on the developed variable-flow strategies was developed. Central energy management tools have been developed for building systems and mine pumping, water supply and air supply networks.



However, no such systems have been developed for the energy management and control of variable-flow in large cooling systems as are found on mines.

### **Integrated simulation model of mine cooling systems**

An existing component-based simulation model of large thermal systems was used and adapted to simulate the energy savings that can be expected by implementing the developed DSM method. The adapted simulation model has not been used before for the purpose of predicting savings based on variable-flow.

### **Case study validation**

The developed strategy and energy management system was implemented on four cooling systems as case studies to validate the feasibility of the new method. It is the first time that an integrated variable-flow method and energy management system was implemented on South African mine cooling systems. It is also the first time that the effects of such methods have been evaluated experimentally on mine cooling systems.

There are significant novel contributions made by this study. It is therefore reasonable that the new contributions have been presented to international audiences by means of peer-reviewed scientific journal articles.

## **1.7 Thesis overview**

The research hypotheses present the key objectives of the study such that the shown needs can be realised and novel research contributions can be made. The layout of the thesis reflects this by being systematically organised as shown below.

### **Chapter 1**

As introduction, a general background is given regarding the electrical energy demand in South Africa. The potential for DSM on mine cooling systems is discussed. It is briefly shown why variable water flow energy saving strategies and new energy management systems show potential on large mine cooling systems. Needs for the study are discussed and the objectives, scope and projected contributions of the study are formulated.

### **Chapter 2**

An overview of large cooling systems is given. This pertains more specifically to large mine cooling systems since the immediate potential has been identified for mine systems. The overview includes descriptions of mine cooling systems and their components, existing energy saving methods, service delivery requirements, system performance considerations, and relevant energy management systems.

### **Chapter 3**

A preliminary investigation to estimate the potential for VSD technology on mine cooling systems is described. This includes an overview of VSD technology and applications, a description of an energy audit done on 20 mine cooling systems and a discussion of estimated results quantifying the saving potential for different VSD applications on mines as well as its economic feasibility.

## **Chapter 4**

The new variable water flow DSM strategy that was proposed to realise energy savings on mine cooling systems is discussed. The strategy addresses the findings of the energy audit done in the previous chapter. The discussion includes descriptions of the control strategies for evaporator, condenser, BAC and pre-cooling water flow rates and the general philosophies behind them.

## **Chapter 5**

An overview is given of the new central energy management system that was developed to suitably integrate the developed variable-flow strategies. The overview includes descriptions of the system architecture, functional specification, control and integration methodology, and monitoring and reporting capabilities.

## **Chapter 6**

To investigate the viability of the proposed strategies before full-scale implementation, a detailed feasibility study was done. This is presented and includes the simulation of the strategies and a cost-benefit analysis. The feasibility discussion is based on the surface cooling system of the Kusasaletu gold mine, the primary case study of the thesis. A description is given of the site and its proposed strategies, the simulation model, its verification by means of comparison to actual measurements, and its output in the form of predicted energy savings. A detailed breakdown of costs, cost savings and economic viability considerations is also presented.

## **Chapter 7**

After viability was shown, the validity of the developed DSM strategy and energy management was investigated experimentally by implementing the strategy on four different cooling systems. The implementation on the primary case study is described in detail in Chapters 7 and 8, while only the key results of the other systems are discussed in Chapter 9.

Chapter 7 focuses on the implementation detail of the strategies through illustration on the Kusasalethu surface cooling system. This includes descriptions of the equipment specified and installed, the energy management system implementation, the measurement procedures and the verification of measurements and results.

## **Chapter 8**

The energy saving strategy is validated by considering the *in situ* experimental results of the Kusasalethu case study. Aspects regarding energy savings and the effects on service delivery and system performance are presented. A detailed discussion of all the results is given to show the influence of the DSM strategy and energy management system. A discussion of the economic viability of the strategy is also given using actual energy savings and costs involved.

## **Chapter 9**

To investigate the validity of the variable-flow strategy in a larger context, the *in situ* results of three more case studies are briefly considered. These include results from cooling systems at Kopanang gold mine and South Deep gold mine (South Shaft and Twin Shaft). Only key results are given and discussed to complement the more detailed case study at Kusasalethu. Furthermore, the expansion of the strategies to large cooling systems in other industries is discussed by considering expansion potential on the Saldanha Steel plant cooling system.

## **Chapter 10**

A consolidating conclusion is given of the study and its integrated results. Relevant study contributions are discussed and recommendations are made for further work.

## Annexures

As mentioned previously, the work that is condensed as research articles (Annexures A-E) is consolidated as a coherent totality in the main thesis monograph. It is important to note that there are invariably many references to the articles to clearly contextualise them. The articles follow on each other to present the research in a similar structure as the thesis chapters. The focuses of the articles are given below.

- Annexure A.1: An investigation of VSD potential and an energy audit of 20 mine cooling systems (complements Chapter 3).
- Annexure B.1: A discussion of the developed variable water flow strategies and simulation model used to predict their potential (complements Chapters 4 and 6).
- Annexure C.1: A description of the new energy management system that implements the variable-flow strategies, including selected results from all four case studies (complements Chapters 5, 7, 8 and 9).
- Annexure D.1: A discussion of the effects of the variable-flow strategies on the energy usage, service delivery and system performance of the Kusasaletu cooling system (complements Chapters 7 and 8).
- Annexure E.1: A summary of the key results discussed in all the preceding articles (complements all chapters).

In general, the articles and the preceding monograph can be considered independently. However, the two entities complement each other and are therefore presented as such. It is suggested that the monograph is considered as the detailed body of the thesis showing all the work that was done; and the articles as summaries of the key results as accepted by and presented in peer-reviewed technical journals.

To simplify the readability of the material, the thesis monograph (Chapters 1-10) is presented in **Volume 1**, while the articles (Annexures A-E) are presented in **Volume 2**.