CHAPTER 10. CONCLUSIONS

10.1 Summary of work done

There are increasing concerns regarding the management and sustainability of global energy resources. A constant electricity demand growth will result in the demand eventually matching the available supply capacity, especially when supply capacities are not adequately managed. Eskom has a DSM programme in place to reduce the South African electricity demand to thereby postpone the predicted date when the demand will reach the generated capacity. It was shown that the mining sector uses 14.5% of the total national electricity demand. It was therefore found that there is considerable potential to investigate new DSM initiatives specifically on South African mines.

Mines require acceptable environmental conditions for underground workers and mining equipment. Therefore, cooling of water and ventilation air sent underground is required. As mining depths increase, so do the cooling demands and the associated technical challenges. Large cooling systems typically consume up to 25% of the total electricity used on South African deep level mines. It was shown that the lack of historic incentive to reduce electrical energy usage on mines led to the typical operation of these cooling systems, presenting opportunities for energy efficiency improvements. Cooling systems of deep mines were therefore found to present good DSM opportunities for the development of new energy saving strategies.

The layout and operation of typical large cooling systems found on deep mines were investigated. This provided insight into the unique operational requirements and potential energy saving opportunities on these systems. Mine cooling system designs were improved over the past 40 years and recent advances were made in load shifting and control improvement of existing cooling systems. However, it was found that more work is required regarding the application of modern energy efficient technology such as VSDs.

Energy saving measures employed in other cooling systems, such as building HVAC systems, were investigated and it was found that variable-flow strategies are widely used. An energy audit was done on 20 South African mine cooling systems to determine the estimated potential for VSD applications in a large context. It was found that the most promising and cost-effective area to focus on is the pumps and fans of these cooling systems. It was also observed that VSDs are not found on mine cooling systems and that these systems are often operated inefficiently. For example, chilled water valve control and water recirculation are common control methods. In general, the cooling demands of most mines seemed to be oversupplied by the present cooling system operational methods.

It was decided to firstly focus on the application of pump VSDs. The formulation of a simple strategy to employ VSDs on the pumps of mine cooling systems was therefore necessary.

A variable water flow strategy employing VSDs on large mine cooling systems would only be successful if the flows can be well modulated according to the thermal loads and unique service delivery and system performance requirements. Mine service delivery requirements were subsequently investigated. It was found that if it is ensured that the specified chilled water temperature and daily volume sent underground as well as the underground ventilation air conditions remain within acceptable limits, there will be no adverse effects on productivity and safety of the mine and its workers.

It would be futile to realise energy savings with system components operating unacceptably inefficient, resulting in long-term cost increases relating to higher maintenance and replacement costs. Mine cooling system performance considerations were therefore also investigated. It was found that factors which typically need to be considered include the acceptable operation of all new control systems, the COP of both the chillers and the integrated system, the cooling efficiency of pre-cooling and condenser cooling towers and BACs as well as the efficiency and performance of the water pumps and the electrical power supply system.

A simple but novel energy saving strategy was subsequently proposed for large cooling systems as found on deep mines. It is based on variable water flow control of auxiliary equipment found on mine cooling systems. The strategy is generic and comprises four measures namely evaporator, condenser, BAC and pre-cooling water flow control.

The evaporator flow control involves modulating the chilled water flow such that a specified chilled dam level is maintained. The condenser flow control modulates the condenser water flow such that a specified water temperature difference across the condenser is maintained. The BAC flow control involves modulating the BAC water flow in direct proportion to the ambient air enthalpy. Finally, pre-cooling flow control entails the modulation of pre-cooling tower supply flow to maintain a specified pre-cooling dam level. These control methods simply ensure that the supply of chilled water matches the demand without unnecessary oversupply.

An energy efficiency strategy is most effectively implemented through the use of a suitable energy management system. Relevant energy management and control systems and strategies currently available were reviewed. It was found that no central energy management system exists that integrates and optimally manages a variable-flow strategy on large cooling systems found on deep level mines. It was also shown that the need exists to develop a system that is simple, robust and practical for industrial applications.

A new energy management system (REMS-CA^{TM}) was developed to implement, control, monitor and report the outlined variable-flow strategies. An overview was given of the system's hierarchical control architecture and its main functionalities. The system is based on a generic approach to energy management and controls strategy set points in real-time from a central location linked to the facility SCADA. It also monitors and reports the energy usage to a variety of stakeholders. The generic system platform is fully customisable and user friendly. The system ensures that the developed generic variable-flow strategies can easily be customised for each site, depending on the requirements, and integrated effectively using the same versatile energy management tool.

The Kusasalethu gold mine surface cooling system was identified as the primary case study to investigate the viability of the proposed strategies and energy management system. The generic strategies were customised for this site to include evaporator water flow control (three pump VSDs), condenser water flow control (three pump VSDs), BAC water flow control (three control valves and three return pump VSDs) and pre-cooling tower replacement. The pre-cooling tower replacement was found to be required on Kusasalethu in order to enable the variable-flow strategies to realise their full potential.

The energy saving feasibility of the strategies on Kusasalethu was investigated through the use of simulated energy saving predictions. An existing cooling system simulation model was adapted. The model was verified by comparing simulated baseline electrical energy usage to actual system electrical energy usage of 2009. The model showed a 6.9% accuracy level. Energy saving predictions were then made by simulating the variable-flow strategies. A simulated annual average saving of 1 779 kW, or 33% of the baseline power consumption, was obtained.

A techno-economic analysis was carried out to determine the economic feasibility of the strategies. The annual cost savings amounted to R8 125 502, while the implementation costs amounted to R5 241 322. The predicted payback period was shown to be eight months, the internal rate of return was calculated as 159% and the net present value (at 15% minimum accepted rate of return) was shown to be R56 650 342. All of these results strongly indicated viability. A sensitivity analysis showed that reasonable changes in electricity tariffs, inflation rate and exchange rate will not be detrimental to the feasibility of the cash flow.

Based on the feasibility results, the strategies and energy management system were implemented at Kusasalethu. The implementation required equipment that suitably adhered to mine standards and did not interfere with mine cooling system infrastructure, production or operation methods during installation or commissioning. Relevant hardware, platform and system control and integration details of the implementation of REMS-CA™ were given. The processes of data acquisition and saving verification were described. The measuring equipment was shown to be suitably accurate, the uncertainty of calculated values was investigated and the process of data measurement was verified. The methods of validating energy savings and data used in the investigation were also verified by an independent auditor as suitably accurate.

In situ implementation results were analysed to investigate the performance of the strategies on the primary case study cooling system of Kusasalethu. For three months of performance assessment, an average daily electrical energy saving of 2 609 kW, or 35.4% of the baseline power was realised. The total saving comprised direct evaporator, condenser and BAC pump savings as well as the saving resulting from a large reduction in daily water volume that needed to be chilled by the chillers.

This water volume reduction resulted from the BAC supply water flow control and the combined effect of shutting off the chilled water back-pass line, installing new pre-cooling towers and controlling the evaporator water flow rate to maintain the specified chilled water dam level.

The service delivery requirements of the cooling system were not compromised by the implementation of the strategies. The chilled water temperature and demand volume sent underground remained within specified limits. The ventilation air temperature and humidity in working areas also did not change significantly after implementation.

The performance of the cooling system and its subsystems was not adversely affected by the implemented strategies. The performance of the newly implemented control system proved suitable and the COPs and operation of the chillers were not varied significantly. The efficiency of the new pre-cooling towers was seen to be much better than the old ones and the efficiencies of the condenser cooling towers and BAC were not reduced. The performances of the pumping and electrical power supply systems were not degraded. Lastly, the COP of the combined cooling system was improved.

The realised annual energy cost saving was calculated to be R9 669 996, leading to a payback period of seven months and an IRR of 188%. These factors verified that the implemented strategy is definitely economically feasible.

The variable water flow strategy and energy management system was subsequently also implemented on the cooling systems of the Kopanang, South Deep South Shaft and South Deep Twin Shaft mines. The key results were presented. Electrical load savings of 31.7%, 29.3% and 33.8% were realised on these systems, respectively. Payback periods were shown to be 10, 17 and five months. For all the case studies considered, it was shown that the critical service delivery requirements such as chilled water temperature, water volumes and shaft wet-bulb temperatures remained within specified limits. On average, an electrical load saving of 33.3% was realised for all four case study systems. This showed that the developed variable-flow strategy and energy management system can effectively be customised for a variety of large cooling systems and realise cost-effective energy savings.

The potential application of the strategy on non-mining industrial cooling systems was investigated by considering a cooling system on the Saldanha Steel plant. Simulated results indicated the possibility of reducing the present electrical load by an annual average of 38.2% with a payback period of 12 months. This showed that the strategy could be extended to realise energy savings on other industrial cooling systems.

The key findings of the integrated investigation were also compiled as a series of research articles, as attached in the annexures. The respective articles focus on the energy audit to investigate the large-scale potential for VSDs on mines, the development of the generic strategies and its feasibility through simulation, the developed energy management system and its application to the four case studies, a more detailed analysis of the Kusasalethu case study and a summary of the entire study.

10.2 Validation in terms of objectives

The reduced problems identified in Chapter 1.5 were addressed as follows: A preliminary large-context energy audit showed that there is significant potential for VSD application on South African mine cooling systems. It showed that pumps and fans are the most feasible areas to focus on. This led to the proposal and development of simple and generic variable water flow strategies to implement VSDs while ensuring that mine service delivery and system requirements are met. A simple, versatile, central energy management system was then developed to integrate the strategies in real-time. The viability of the new energy saving strategy was investigated through the use of an adapted simulation model and a cost-benefit analysis. It was shown that the strategy is feasible. The strategy was subsequently implemented and the viability was proven by verified experimental results on a primary case study and three secondary case studies, indicating significant energy savings (33.3%) without adversely affecting system requirements and service delivery. The potential of expansion to other industrial cooling systems such as a large air-cooled heat exchanger cooling system was also shown.

The research hypothesis was proven by showing that **a variable water flow strategy will realise energy savings in large cooling systems without adversely affecting service delivery and system performance**. Moreover, a new such strategy was developed and successfully implemented, realising the main research objective.

10.3 Contributions to the field

The definite need for the further development of DSM initiatives on mine cooling systems was the incentive for this study. It was found that the energy efficiency of these large systems can be improved upon. Through investigations it was found that VSDs are not found on these systems, nor have large-scale studies been done to investigate its potential. Energy saving strategies aimed at matching the cooling supply to the demand through variable water flow have not been developed for these systems, nor have an energy management system to implement it been developed. This study addressed these needs for the first time in internationally published literature.

The preliminary investigation and energy audit done on 20 South African mine cooling systems to determine the large-scale potential of VSDs is the first of its kind in published literature. The findings of this investigation are novel because it discusses and quantifies the estimated potential of VSDs in a large context on South African mine cooling systems for the first time. The results will be useful to energy managers and decision-makers that are considering energy efficiency improvements, something that is critically important in the modern society.

The developed variable water flow strategy describing simple control methods for evaporator, condenser, BAC and pre-cooling water flow is novel. No such methods have previously been proposed, developed, implemented or analysed experimentally for large cooling systems found on South African mines. The strategy forms the core of the study and, although developed specifically for large mine cooling systems, potential to expand it to non-mining industrial cooling systems was also shown.

The developed central energy management system that integrates, controls, monitors and reports on the developed variable-flow strategies is new. No such systems have been developed or published for the energy management and control of variable-flow in large cooling systems as found on mines.

The adaptation and use of the existing component-based simulation model to predict energy savings specifically for this strategy was done for the first time. The adapted simulation model has not been used for the purpose of predicting savings based on variable-flow before.

The implementation of the developed strategy and its energy management system on four cooling systems is novel. It is the first time that an integrated variable-flow method and energy management system has been 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 and published internationally.

The overall result of the study was that a new variable water flow strategy was presented for energy savings on large cooling systems and that an average measured energy saving of 33.3% was realised on four different large cooling systems without adversely affecting the system performance and service delivery. This underlines the significant contribution made to the field of new DSM initiatives, specifically applied to large cooling systems. In a larger context, a definite contribution was made towards the improvement of industrial energy efficiency and sustainability in South Africa and globally through the published articles.

10.4 Aspects meriting further investigation

It was shown that commercial building HVAC systems have made more energy efficient advances in recent years than large industrial cooling systems as found on South African mines. This study addressed the DSM opportunity of developing and installing variable water flow strategies on mine cooling systems by using modern VSD technologies. It adds to the existing research contributions towards sustainable large cooling system energy management which includes load shifting measures and ice dam thermal storage initiatives. However, recommendations for further studies in this field can be made.

First, it is advised to implement the DSM strategy and energy management tool developed in this study on large cooling systems outside the mining industry. It was shown by an investigation and simulated results of the Saldanha Steel plant that there is definite potential for such an extension. It remains to be investigated further, implemented and analysed on more industrial cooling systems.

Second, a more detailed investigation of mine BACs on surface and underground is advised. This study showed the negligible effects that significant BAC water flow reductions had on underground ventilation air conditions. It follows that it will be worthwhile to re-evaluate the original designs of underground thermal resistance networks and investigate alternative possibilities such as BAC load shifting or further water flow control measures.

Third, the integrated operation of various cooling systems and the combined water reticulation deserves further investigation. Most present DSM initiatives only consider a specific control volume of this network, using the given subsystem boundaries as parameters. It is believed that further optimisation is possible by considering the whole system and the effects of a given subsystem change on the integrated water reticulation network. For example, the control of underground water valves according to real-time demands and its instantaneous effect on the surface and underground cooling systems as well as underground pumps can be investigated. An optimised solution to efficiently control the entire water reticulation network by a single controller would be a significant research contribution.

Finally, it is recommended to investigate further opportunities to retrofit inefficient subsystems of large mine cooling systems with modern energy efficient equipment as a continuation of this study. VSD retrofits should be extended to fans and possibly chiller compressors as suggested by the preliminary investigation in this study. Further possibilities in this regard might include modern, energy efficient cooling tower designs and efficient maintenance plans such as clean-in-process plans for heat exchangers and pipes that often have high fouling rates.

The proposed investigations will make valid contributions to the existing knowledge pool of this field. This is necessary because a continuous energy-conscious review is required if the changing needs of the mining industry and specifically of large cooling systems are to be met.

10.5 Conclusion

It was shown that DSM potential exists to implement VSDs and improve the energy efficiency of large cooling systems such as found on South African mines. A variable water flow strategy that includes a new central energy management system was developed in this study to realise electrical energy savings on these systems. The strategy was implemented on the surface cooling system of the Kusasalethu mine as a primary case study. The obtained *in situ* results showed that the strategy realised significant savings without compromising service delivery or system performance. Three secondary case studies confirmed this. Over a period of three months, average electrical load savings of 606-2 609 kW (29.3-35.4%) were realised on the four systems with payback periods of 5-17 months. The average electrical load saving between the sites was 33.3% at an average payback period of 10 months. The potential for strategy extension to other industrial cooling systems was also shown. The study therefore validated the developed strategy as a viable, novel energy saving measure on large cooling systems, contributing to the advancement in the management and sustainability of energy resources.