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A variable water flow strategy for energy savings in large cooling systems

Volume 2: Research articles

GE du Plessis

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Thesis submitted in fulfilment of the requirements for the degree *Philosophiae Doctor* in Mechanical Engineering at the Potchefstroom Campus of the North-West University

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September 2013

It all starts here

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ANNEXURES: RESEARCH ARTICLES

The annexures present the five research articles that were compiled to summarise the key findings of the study presented in the thesis report. The articles follow logically on each other in the same general structure presented by the report. Each article can be considered independently. They were presented to the relevant journals independently and some repetition regarding background is therefore unavoidable. However, the core focus of each article is unique and complements the important results of the integrated study. Applicable articles are followed by relevant license and reprinting permission agreements as well as journal editorial requirements.

A summary of the articles is given in Table i.

Table i Research articles overview

Article	Research objectives	Method	Main findings and conclusions
1. The use of variable speed drives for cost-effective energy savings in South African mine cooling systems	- To estimate the large-scale potential of variable speed drives (VSDs) on South African mine cooling systems - To identify the most important areas for VSD use - To validate the findings through a preliminary pilot case study	- Energy audit of 20 South African mine cooling systems - Calculation of estimated energy, cost and greenhouse gas emission savings - Implementation and results analysis of VSDs on the South Deep mine	- A total annual electrical energy saving of 32.2% (144 721 MWh) is estimated for the 20 mines - The most feasible VSD target areas are cooling system pumps and fans - Case study VSD implementation shows 29.9% saving
2. The development and integrated simulation of a variable water flow energy saving strategy for deep-mine cooling systems	- To develop a variable water flow control strategy that enables energy savings through VSD implementation on mine cooling system pumps (as recommended by Article 1) - To simulate the developed strategy and validate the simulated results	- Strategies to control mine cooling evaporator, condenser and bulk air cooler water flow based on mine-specific cooling demands - Existing component-based simulation model adapted, verified and used to predict energy savings on the Kusasalethu mine	- An electrical energy saving of 33% is predicted by implementing the strategy at Kusasalethu - The simulation model predictions are shown to be accurate to within an average of 7%
3. A versatile energy management system for large integrated cooling systems	- To develop a robust and practical energy management system that integrates the control strategies developed in Article 2 - To experimentally evaluate the system by *in situ* application on four different mine cooling systems	- Real-time Energy Management System for Cooling Auxiliaries™ developed as a hierarchical controller - Main features are to automatically control, optimise, monitor and report the variable-flow strategies - Implementation on four cooling systems	- System links to existing SCADA and writes out optimal set points to be controlled by PLCs in real-time - An average of 33.3% electrical energy saving is realised for the four different cooling systems - The average payback period is 10 months
4. Case study: The effects of a variable water flow energy saving strategy on a deep-mine cooling system	- To experimentally evaluate the effects of the strategy and energy management system described in Article 2 and Article 3 - To evaluate the energy savings as well as the effects on service delivery and system performance	- Strategy and energy management system implemented at Kusasalethu mine - Electrical energy savings measured - Changes in chilled water temperature, chilled water volumes, ventilation air conditions and coefficients of performance (COPs) evaluated	- An average electrical energy saving of 31.5% is realised for one month - Chilled water and ventilation air service delivery are maintained within acceptable limits - System performance and COPs are maintained within acceptable limits - Payback period of nine months
5. Improved energy efficiency of South African mine cooling systems	- To describe the improved energy efficiency through the newly developed variable-flow strategy and energy management system - To summarise the key findings of Article 1 to Article 4	- Large-scale energy audit and VSD potential investigation - Variable water flow strategy and simulation development - Energy management system development - Implementation on four cooling systems	- Pumps show best VSD potential - Strategy matches mine cooling supply with the demand - Energy management system integrates substrategies in real-time - Average energy efficiency improvement of 33.3% on all sites

Annexure A.1

The use of variable speed drives for cost-effective energy savings in South African mine cooling systems

- G.E. du Plessis, L. Liebenberg, E.H. Mathews

- Applied Energy, 2013

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This article focuses on the preliminary investigation done on 20 South African mine cooling systems to estimate the general potential of VSDs on these systems. The investigation results complement Chapter 3. Pilot implementation results specifically concerning pump energy usage at South Deep South and Twin Shafts are presented as validation. This complements selected case study results of Chapter 9.

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The use of variable speed drives for cost-effective energy savings in South African mine cooling systems

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HIGHLIGHTS

- Energy analysis of 20 South African mine cooling systems.
- Energy savings and feasibility calculated for large-scale variable speed drive implementation.
- An annual electricity saving of 144,721 MW h (32.2%) and CO_2 emission reduction of 132 Mton can be realised.
- Pump and fan application found more viable than chiller application.
- Pilot implementation study shows pump electricity savings of 29.9%.

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ABSTRACT

An industrial energy efficiency improvement through the introduction of modern technology is an important demand-side management initiative. Cooling systems on South African mines have been identified as large electricity consumers. There is significant potential for energy efficiency improvement by the widespread introduction of variable speed drive (VSD) technology. An energy audit was conducted on 20 large mine cooling systems and potential savings and feasibility indicators were calculated. A pilot implementation study was also done on one mine to experimentally validate the estimated savings. In this paper, the results of the audit, the potential savings and the pilot study results are presented. It is shown that large-scale implementation of VSDs on mine cooling system pumps and fans is economically viable. A total annual electrical energy saving of 144,721 MW h, or 32.2%, can be achieved. An annual cost saving of US$6,938,148 and CO_2 emissions reduction of 132 Mton is possible. The implementation of VSDs on mine chiller compressors will also result in large energy savings, but is not economically feasible at present. Results of the pilot study indicate an electricity savings of 29.9%. The results are important to decision makers and indicate the significant impact that widespread VSD usage on mine cooling systems can have on South African mine sustainability.

1. Introduction

Improving the energy efficiency of industrial energy users is of global importance. Industry, including the mining sector, uses 37% of the world's total produced energy [1]. Worldwide industrial energy consumption is expected to grow at an average of 1.4% per year over the next 25 years [2].

In South Africa, the rapid increase in economic growth, industrial output and power distribution to previously disadvantaged communities has led to a large increase in electricity consumption since 1993 [3]. The country presently generates 43% of Africa's total electricity [4]. The majority of this electricity is generated by burning coal, making South Africa the 7th largest emitter of greenhouse gas (GHG) emissions per capita in the world [5].

The South African government has pledged a GHG emission reduction of 34% by 2020 [6]. One of the key national plans to achieve this, while avoiding reduced economic growth, is to improve industrial energy efficiency [7,8]. Studies have shown that there is still significant scope for widespread energy efficiency improvements, specifically by focussing more closely on high-demand sectors [3].

Energy efficiency improvement through new technology is an important and usually significant demand-side management (DSM) initiative in industrial systems [1,9]. More specifically, the installation of variable speed drives (VSDs) on chillers, pumps and fans has indicated significant cost-saving potential [10–12]. It has been shown that it is viable to extend the use of VSDs in

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Nomenclature

BAC	bulk air cooler
C_{VSD}	total VSD implementation cost (US$/year)
CCE	cost of conserved energy (US$/MW h)
COP	coefficient of performance
CS_{VSD}	total annual cost savings after VSD implementation (US$/year)
DSM	demand-side management
$EC_{chiller}$	chiller electrical energy consumption before VSD implementation (MW h)
$EC_{chiller,VSD}$	chiller electrical energy consumption after VSD implementation (MW h)
$EC_{pump,fan}$	pump or fan electrical energy consumption (MW h)
EF_{CO_2,SO_2,NO_x}	GHG emissions factor for specific fuel used (kg/MW h)
$ES_{chiller}$	annual chiller electrical energy savings after VSD implementation (MW h/year)
$ES_{pump,fan}$	annual pump or fan electrical energy savings after VSD implementation (MW h/year)
ES_{VSD}	annual electrical energy savings after VSD implementation (MW h/year)
ESP	energy saving percentage associated with speed reduction (%)
ET	electricity tariff (US$/MW h)
ER_{CO_2,SO_2,NO_x}	annual GHG emission reduction (kg/year)
$\%F$	percentage of specific fuel used for electricity generation (%)
GHG	greenhouse gas
$IGBT$	insulated gate bipolar transistor
LF_c	cooling loading factor
LF_p	pump or fan power loading factor
OH	operating hours (h)
PWM	pulse width modulation
PBP	payback period (years)
$\dot{Q}_c$	chiller rated cooling capacity (MW)
VSD	variable speed drive
$\dot{W}_{rated}$	pump or fan power rating (MW)

chillers and their subsystems, especially in large-scale applications [10,13].

The mining industry is a major role-player in the South African economy. This sector is extremely energy intensive, accounting for 14% of the national electricity supply [14]. Cooling systems are responsible for up to a quarter of the electrical energy consumed at a typical deep level mine [15]. These cooling systems continuously supply chilled water and cold ventilation air to the mine to ensure acceptable underground operational and working conditions for employees and equipment.

Various studies have been conducted regarding energy and cost reductions on mine cooling systems [15–18]. Integrated energy management software for large cooling systems has been developed that can be applied to mine cooling [19]. The effects that variable water flow have on mine cooling service delivery were also shown for a specific case study [20]. However, it has been found that modern energy efficient technologies, more specifically VSDs, are not widely used in South African mine cooling systems. Although there is significant potential to introduce VSDs on many if not all of these systems, a large-scale investigation has not previously been done to evaluate and quantify the potential energy, environmental and cost benefits that might be realised.

This paper therefore investigates the large-scale potential for VSDs on South African mine cooling systems. Energy consumption of chillers, pumps and fans are evaluated and potential energy, cost and GHG emission savings are estimated. Feasibility indicators such as payback period and cost of conserved energy are also calculated. A large-scale energy evaluation of 20 mine cooling systems is supported by validating pilot implementation results. The main objective is to investigate the potential large-scale impact of installing VSDs on mine cooling systems and its contribution to improving South African industrial energy efficiency and sustainability. The results reported by this study can be used as a guideline to energy managers, especially in the South African mine industry, to improve cooling system energy efficiency through the use of VSDs and to increase industrial awareness of VSDs and their widespread applications.

2. Variable speed drive considerations

It is appropriate to review the state-of-the-art in VSD technology, its potential benefits, and considerations when evaluating its feasibility. This is important in context of the effective investigation of its potential on mine cooling systems.

2.1. Energy saving potential

Electric motors have high efficiencies when operating at rated loads. However, it has been shown that almost half of all industrial motors are loaded below 40% rated capacity, resulting in reduced operating efficiency [21]. Variable duty requirements of systems such as pumps, fans and chillers have traditionally been controlled by inefficient methods such as bypass and recirculation pipelines, throttle valves and flow dampers, using constant-speed electric motors [13].

Various studies have shown that using variable speed electric motors is the most efficient and promising method of operating a given load and realise energy savings [22,23]. For example, the increased frictional resistance and pressure drop as a result of valve control can be eliminated or reduced significantly when opening the valve fully and modulating the flow by VSD control instead. It has been shown that for pump systems that operate for more than 2000 h/year, using VSDs to control flow instead of valves will almost always lead to significant life-cycle cost savings and environmental benefits [24].

A VSD is connected between the driven electric motor and the power supply system. It essentially consists of a multi-phase diode rectifier, a control and protection regulator and an inverter with insulated gate bipolar transistor (IGBT) components. Pulse width modulation (PWM) is used to create variable voltage, current and frequency as output to the motor and thereby allows the regulation of speed, torque and power [25].

As a result of significant advances in semiconductor technology, design improvement and intelligent control features, the use of VSDs has become increasingly popular in recent years [26–28]. Successful implementation and optimisation in various sectors have been vindicated, as shown by studies on a refinery [29], cement plant [30], boiler house [31], petroleum plant [32] and conveyor systems [33,34].

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 [25]. This concept is illustrated in Fig. 1,

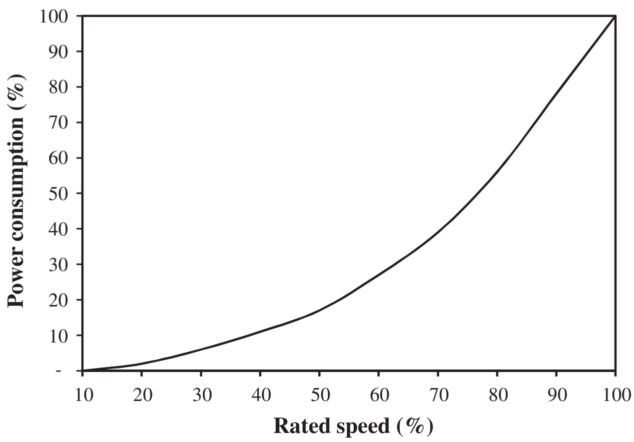

Fig. 1. Electric motor power consumption as a function of speed [35].

Table 1
Typical chiller compressor VSD costs (in US$) in South Africa.

	Voltage (V)	800 kW	1000 kW	1500 kW	Average
Company A	6600	155,125	182,859	240,699	
Company B	6600	164,470	195,019	250,351	
US$/kW		200	189	164	184
Company A	11,000	222,642	250,373	335,815	
Company B	11,000	224,423	265,315	333,756	
US$/kW		279	258	223	253
Installation		9650	9650	9650	
US$/kW		12	10	6	9
US$/kW (6600 V total)		212	199	170	194
US$/kW (11,000 V total)		292	268	230	263

which shows typical real electric motor power consumption as a function of rated speed [35].

VSDs can therefore be an important energy efficiency measure on cooling systems which usually consist of variable torque subsystems. Various studies have been done in this regard. A variable speed pumping scheme was investigated for an academic building chiller system by Tirmizi et al., realising energy savings of up to 13% [36]. Crowther and Furlong showed how variable speed cooling tower fans can also save energy [37]. Qureshi and Tassou confirmed that capacity modulation by applying VSDs to chiller compressors can lead to 12–24% energy savings [12]. Energy savings of 19.7% were presented by Yu and Chan for all-variable speed chiller systems [11]. Common set point requirements used to control VSDs include chiller compressor lift, chilled and cooling water supply pressure, water temperature and water tank levels, depending on the system requirements.

In addition to energy savings, VSDs also present other potential benefits. These include process control improvement [38], system performance and reliability improvement [25], soft starting and stopping, reduced maintenance [39], electric motor and system life extension [40] and power factor correction [41].

2.2. Economic factors

It is important to consider economic factors when evaluating the feasibility of energy efficient technology acquisition. These include the initial capital requirements, the return on investment and the cost per energy saving realised.

The rise in VSD popularity has led to a significant cost reduction in recent years. Low-voltage pump and fan VSD costs of about US$96/kW for a 37 kW unit and US$84/kW for a 745 kW unit were reported in the United States of America during 2011 [42]. Consultation, cabling, installation and commissioning costs were shown to be about US$133/kW in Turkey during 2004 [31]. However, this cost was applicable to the installation of only one 30 kW VSD and is therefore relatively conservative. Similar labour costs will be involved for larger drives and typical costs per kW can be expected to be proportionally lower.

Table 1 shows typical costs associated with medium-voltage VSDs applicable to mine chiller compressors in South Africa. These are costs of VSDs with standard panel protection and essential harmonic filtering equipment. Some chiller compressors have impeller blades that are designed for a very wide range of cooling loads. Other blade designs, especially older ones, accommodate only small load ranges. In these cases it is necessary to suitably alter or replace the impeller and possibly also replace the expansion valve to prevent compressor surges and allow efficient refrigerant flow modulation over the range planned for with the VSD. The average costs of these typical modifications were included in the VSD costs in Table 1 because most mine chillers are older than 15 years. Shown installation costs include typical cabling, programming control adjustments and commissioning requirements.

Table 2 shows typical costs of low-voltage drives applicable to most pumps and fans in South Africa.

Tables 1 and 2 show that VSD cost per kW decreases with increasing power rating. It can also be seen that medium-voltage drives are significantly more expensive than low-voltage drives. Therefore, the benefits of chiller VSDs should be carefully considered before purchase. VSD costs in South Africa are higher in comparison to prices abroad. This can be attributed to the importing costs and the relatively low demand for VSDs in South Africa. However, installation costs are generally relatively low in South Africa.

Cost-effectiveness is commonly indicated by the payback period (*PBP*) as calculated by Eq. (1) [25] and Eq. (2) [1].

$$PBP = \frac{C_{VSD}}{CS_{VSD}} \quad (1)$$

where

$$CS_{VSD} = (ES_{VSD})(ET) \quad (2)$$

It is important that the total incremental cost of implementation (C_{VSD}) includes VSD costs as well as costs associated with necessary system changes, implementation and commissioning. Also,

Table 2
Typical pump and fan VSD costs (in US$) in South Africa.

	Voltage (V)	75 kW	132 kW	160 kW	200 kW	275 kW	Average
Company A	525	17,442	23,231	26,445	31,499	45,003	
Company B	525	10,191	13,740	15,798	17,572	22,104	
Company C	525	8446	13,045	14,920	19,060	23,008	
Company D	525	10,486	14,086	15,058	18,260	25,044	
US$/kW		155	121	113	108	105	120
Installation		3355	3355	3355	3355	3355	
US$/kW		45	25	21	17	12	24
US$/kW (total)		200	147	134	125	117	144

hourly energy savings and tariffs must be taken into account when calculating cost savings (CS_{VSD}). This is because electricity tariffs (*ET*) are based on time-of-use in South Africa.

It has been shown that a *PBP* of less than one third of the expected electric motor life should be considered viable [1]. Typical feasible *PBP*s for VSDs have been reported as less than 2 years [28,31].

A further measure of cost-effectiveness is the annual cost of conserved energy (*CCE*) as calculated by Eq. (3) [42].

$$CCE = \frac{C_{VSD}}{ES_{VSD}} \quad (3)$$

A *CCE* value of US$43/MW h has been reported for VSD installations, indicating that it is one of the most feasible energy efficient measures available [42].

2.3. Potential barriers

Factors that have been found to impede the widespread usage of VSDs include technical, economic and awareness barriers. It is important to be aware of these possible pitfalls and their suggested mitigation measures when evaluating new VSD applications.

The operation of VSDs imposes non-linear loads on power distribution systems. This may lead to problems such as the generation of harmonic voltage and current distortion into the mains supply and radio frequency interference with susceptible equipment. Harmonic distortion not only results in wasted power but also leads to overheating of equipment, decreased motor efficiencies, circuit breaker tripping, premature failure of old motors and communication network errors [13].

Modern VSD features have been developed to mitigate potential technical problems. Typical measures to reduce harmonic distortion include line reactors, input and motor chokes, multi-pulsed systems and active and passive filters [25]. Connector cables should also be shielded and as short as possible while proper grounding must be applied throughout [10]. Technical concerns are mostly unjustified if a VSD is correctly specified and installed for the specific application.

Economic considerations can also lead to VSD project proposals being rejected. Even though VSD costs have decreased, it is still relatively expensive technology. Budgets do not always cater for such costs, especially in organisations where there are split budgets between departments. This may lead to payback periods in excess of 3 years. These issues can be addressed by financial incentives such as rebate structures [25] and organisational financial rewards for savings realised. Although such structures can be very effective, it is important that rebates and savings be appropriately quantified for energy saving applications [10].

There is generally a high level of industrial awareness of VSDs. However, technical personnel are often sceptical about the actual achievable energy savings and concerned about the risks involved. Existing promotional and supporting publications often do not match the user requirements well. It has been suggested that to improve awareness, incentives should be aimed at the needs of sector-specific motor users. These may include independent seminars, calculation software and simple printed or electronic educational tools. It is also important to report successful case studies and results of investigations that accentuate the mitigation of problems and the true benefits of VSDs [10].

Motor users and plant personnel are often also concerned about the after-sales implications that VSDs have such as maintenance requirements, staff training and breakdown support. Maintenance requirements of VSDs are negligible, with the only typical annual replacements necessary being air intake filters. If the drive is specified and installed correctly, there should be no regular maintenance requirements. All surveyed manufacturers also include a 12-month warranty, full breakdown support and training of all relevant plant staff in the VSD costs shown in Tables 1 and 2. These manufacturers also indicated that they offer annual VSD inspections and repairs if necessary at about US$10/kW. It is thus apparent that after-sales concerns are generally unwarranted, given that the drives are suitably implemented.

3. Investigation

South African mine cooling systems were investigated to evaluate typical operation, available technology, energy consumption and potential savings that can be realised from VSD installations. The focus was on estimated VSD potential in the larger context, rather than on site-specific flow control strategies and effects, as reported elsewhere [20].

3.1. Mine cooling systems

Chilled water is needed in deep mines for various purposes. These include bulk cooling of ventilation air, cooling of rock drills and other machinery, rock sweeping operations, dust suppression and underground cooling cars or spot coolers [43]. The combined cooling capacity required is typically 30 MW or more [44]. Large and uniquely designed, integrated cooling systems are required. These systems are installed both on the surface and underground as integral parts of typical semi-closed loop mine water reticulation systems [45]. Fig. 2 schematically shows a typical surface cooling system.

Hot water from end-users and underground drainage water enters storage dams at 30–35 °C from where the water is pumped through pre-cooling towers. These are usually forced draught direct heat exchangers that cool the water down to just above ambient temperature [46]. The pre-cooled water is then pumped through large water-cooled chillers where the temperature is reduced to approximately 2 °C. The arrangement and size of the chillers depends on the requirements of each specific mine. Chiller cooling water is pumped through a set of condenser cooling towers where heat is transferred to ambient. In mine cooling systems electrical energy is therefore consumed mostly by variable torque turbo machinery, as shown in Fig. 2.

Chilled water is either sent directly to the working face and various underground end-users or pumped through bulk air coolers (BACs) [47]. A BAC is a direct contact heat exchanger that uses chilled water to cool ambient air before it is sent down the shaft for ventilation purposes. A typical BAC outlet air wet-bulb temperature of about 8 °C usually ensures that the legally required wet-bulb temperature of 27.5 °C or less is maintained on deep underground production levels [48].

Demand for chilled water underground is sporadic as a result of the complex network of end-users and underground working shifts. Chilled water storage dams ensure that the varying demands of the mine can be met [49]. The network of storage dams is usually interconnected to allow the bypass and/or recirculation of water as required by variations in operating conditions.

Improving the energy and cost-efficiency of mine cooling systems have been investigated by various studies. Pelzer et al. [16] developed a strategy that reduces and controls the inlet water temperature of chillers to improve the chiller coefficient of performance (COP). Swart [17] and Van der Bijl [18] 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 potential for further energy efficiency improvements through new technology such as VSDs.

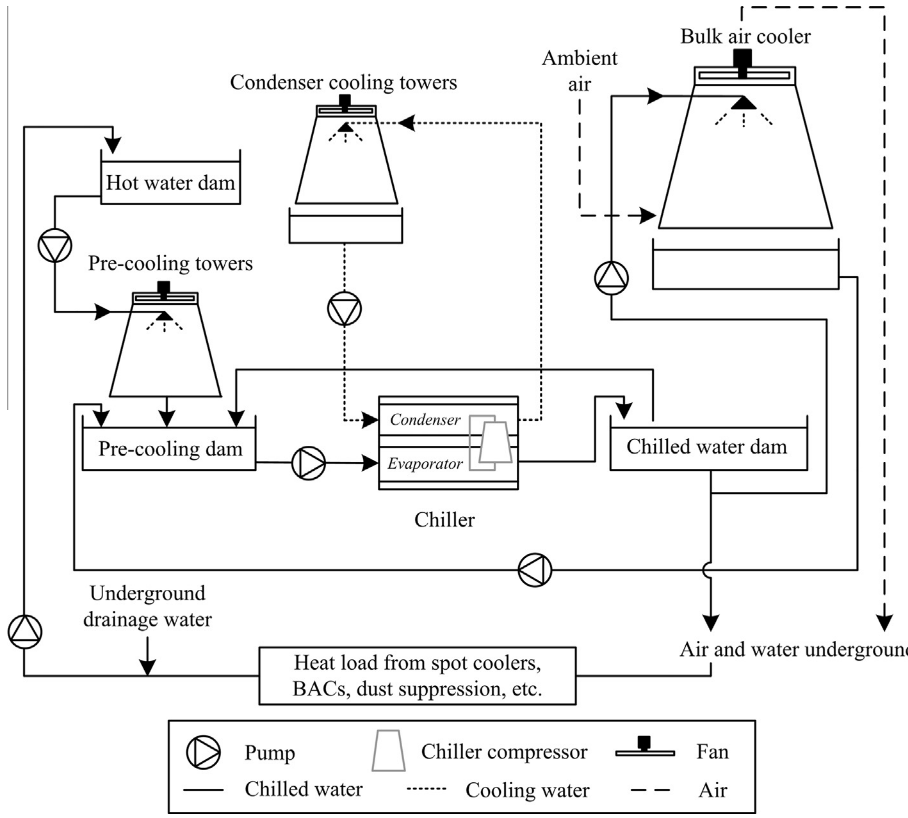

Fig. 2. Typical mine surface cooling and chilled water supply system.

3.2. Energy audit

A comprehensive energy audit is a key step in systematic energy management [50]. Twenty mine cooling systems were audited to evaluate their present features, operation and energy consumption. Detailed site visits were conducted to evaluate the systems. Meetings were also held with relevant managers, foremen and operators to obtain further information.

Logged system data, typically over a period of 1 year or more, were obtained from mine personnel. This was used in conjunction with design specification sheets and other relevant material [51,52] to analyse subsystem loading and energy consumption. Electrical energy consumed by a chiller and pump or fan can be calculated from Eq. (4) [53] and Eq. (5) [54], respectively.

$$EC_{chiller} = (OH)(\dot{Q}_c)(LF_c)(COP^{-1}) \tag{4}$$

$$EC_{pump,fan} = (OH)(\dot{W}_{rated})(LF_p) \tag{5}$$

The chiller cooling load factor is the ratio of the actual thermal load to the full design cooling load. The power load factor of a pump or fan electric motor is the ratio of actual capacity to rated capacity. Average load factors of the subsystems on each site were used in Eqs. (4) and (5) and were calculated from measured loads and load profiles. The key results of the evaluation are shown in Table 3.

It can be seen from Table 3 that 112 large chillers were evaluated with individual cooling capacities varying between 3 MW and 16.4 MW, with COP values between 3 and 6.5. Chiller loading factors varied somewhat depending on seasonal effects and operation methods of the individual mines. The average cooling load factor was 75.7%. Chillers account for 66% of mine cooling system electricity consumption.

Standard equipment on the audited sites included chilled water pumps, condenser cooling water pumps and various transfer pumps supplying water to pre-cooling towers and BACs. These are low-voltage centrifugal pumps with installed capacities varying between 50 kW and 600 kW. These pumps operate at an average loading factor of 82.4% and account for 27% of total cooling system electricity consumption.

Axial fans were found to be installed on pre-cooling towers, condenser cooling towers and BACs. Installed capacities varied between 40 kW and 400 kW. Some of these fans, such as those on BACs, were shut down during winter months when they were not required. The fans operate at an average load factor of 85.4% and comprise only 7% of the total electricity consumption.

A typical mine cooling system consists of 4–5 chillers, 5 chilled water pumps, 5 cooling water pumps, 4 transfer pumps and 5 cooling tower fans. The average site installed capacity was 10.8 MW and the average annual electricity consumption was 65,911 MW h. The total annual electricity consumption of the evaluated sites was 1,318,225 MW h. This is 4.0% of the total electrical energy used by all mines in South Africa and 0.6% of the total national electricity supply.

No VSDs were installed on any of the electric motors of these mine cooling systems. These mines comprise about 80% of deep mines in South Africa and include all the leaders regarding mining innovation and technology. It can therefore be assumed that no deep-mine cooling system in the country uses VSDs.

Possible reasons for the lack of VSD acceptance were investigated. At some mines personnel were concerned about the technical problems that VSDs might cause. In most cases however, it was found that there was a general lack of awareness and initiative. It is believed that this can be attributed 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

Table 3
Annual electrical energy consumption of selected South African mine cooling systems.

Site	Chillers				Pumps			Fans			Total
	Qty.	Cooling capacity (kW)	Cooling load factor (%)	Total energy consumption (MW h/year)	Qty.	Load factor (%)	Total energy consumption (MW h/year)	Qty.	Load factor (%)	Total energy consumption (MW h/year)	Total energy consumption (MW h/year)
1	4	13,300	76	46,719	14	74	10,996	4	90	2120	59,835
2	6	6500	80	41,099	19	82	13,679	8	75	4504	59,282
3	4	5000	69	19,320	10	75	7406	5	93	3478	37,158
	1	6000		6955							
4	4	6000	67	25,292	15	70	10,499	4	74	2650	38,440
5	4	11,500	79	44,436	14	86	14,010	9	94	11,526	78,827
	1	5500		8855							
6	3	5000	92	15,807	16	97	12,619	13	81	8280	59,923
	2	5000		10,538							
	1	14,000		12,679							
7	3	7500	74	20,700	19	81	16,858	13	89	7187	71,379
	1	10,500		9660							
	1	16,400		16,974							
8	2	10,000	78	18,400	12	83	7525	7	79	6359	47,924
	1	5000		4600							
	1	12,000		11,040							
9	3	11,000	84	31,878	15	91	9505	12	99	9539	55,172
	1	4400		4250							
10	4	10,100	62	34,949	16	69	21,859	7	71	8280	98,949
	6	3700		33,861							
11	4	6600	71	27,821	11	88	8214	4	87	5299	41,334
12	4	4150	92	25,319	10	95	23,846	1	94	1656	88,801
	6	4150		37,979							
13	2	5000	89	16,100	6	86	10,433	2	96	2517	29,050
14	3	6450	82	24,923	8	80	13,116	3	75	3974	42,013
15	6	3000	61	29,808	22	79	51,005	4	91	1855	112,476
	3	6000		29,808							
16	5	5340	65	26,914	12	78	25,171	4	78	4306	56,390
17	2	10,000	73	21,955	8	79	20,137	3	74	3974	46,066
18	8	6000	90	84,562	7	91	12,321	1	99	874	97,757
19	12	4000	58	86,940	16	81	42,394	4	96	5299	134,633
20	4	10,000	71	38,640	10	83	22,190	2	73	1987	62,818
Total	112		75.7	868,780	260	82.4	353,781	110	85.4	95,664	1,318,225
(%)				66			27			7	100

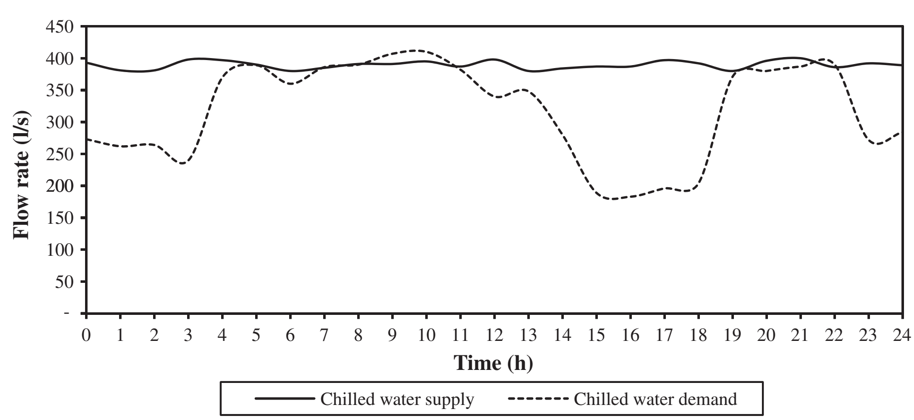

Fig. 3. Typical measured daily profile of mine chilled water demand and supply at present.

pursuing energy saving measures. This appears to still be the case among most technical personnel.

Loading and scheduling operations were observed to be mostly inefficient on mine cooling systems. Typically inefficient flow control measures are common, most motors are oversized and operate at moderate loading factors and chillers are not operated optimally for given loading conditions. Furthermore, part-load conditions were identified on all systems. This was primarily due to daily ambient condition fluctuations and the intermittent nature of water usage underground. For example, Fig. 3 shows the typical daily profiles of the chilled water demand and supply measured at one of the audited sites.

Fig. 3 shows that the supply flow is constant while the demand flow is intermittent. The fluctuations in the demand profile are caused by scheduled water-consuming underground operations, such as drilling and cleaning shifts. The supply flow is maintained constant at the maximum possible flow and all overflow water is recycled to the chiller inlet. In this example, the average demand is 18% lower than the supply. One could consider applying optimal pump scheduling techniques [55]. However, most mine personnel and energy managers indicated that they would prefer continuous flow control because of the added process control benefits of VSDs. The frequent starting and stopping of fixed speed equipment should also be avoided when possible due to the increased wear associated with it. It is thus apparent that there is definite potential for flow modulation by VSD to match the actual load profile of the chilled water demand.

From the energy consumption results, inefficient operations and part-load conditions it is apparent that there should be significant potential for changing over to VSDs on these cooling systems. However, viability must be investigated by estimating savings and feasibility parameters.

3.3. Saving estimates

It is of utmost importance that savings estimations are made correctly and conservatively so as to not make poor business decisions [56]. Various methods have been used to estimate potential savings that can be realised after installing VSDs on chiller compressor, pump and fan motors. A simplified approach described by Saidur et al. [57] was adopted because of its suitability to large-scale evaluations.

Energy consumption of variable speed chillers can be estimated by using Eq. (4) and considering variable speed chiller performance changes regarding the COP for different loading factors [51,52]. The energy savings that can be realised under the same operating conditions are then calculated from Eq. (6) [58].

$$ES_{chiller} = EC_{chiller} - EC_{chiller,VSD} \tag{6}$$

Estimates for pump or fan energy savings when using VSDs can be calculated using Eq. (7) [35]. Energy saving percentage (*ESP*) values associated for various speed reductions can be found in Ref. [35].

$$ES_{pump,fan} = (OH)(\dot{W}_{rated})(ESP) \tag{7}$$

Reductions in energy usage also result in reduced GHG emissions associated with electricity generation [59]. Estimates for the reduction in CO_2, SO_2 and NO_x emissions as a result of relevant energy savings (*ES*) can be calculated from Eqs. (8)–(10) [1].

$$ER_{CO_2} = (ES)\sum(\%F \times EF_{CO_2}) \tag{8}$$

$$ER_{SO_2} = (ES)\sum(\%F \times EF_{SO_2}) \tag{9}$$

$$ER_{NO_x} = (ES)\sum(\%F \times EF_{NO_x}) \tag{10}$$

Emission factors are based on electricity generation by burning coal [14]. This accounts for 92% of South Africa's electricity [60]. Emission reduction estimates are therefore conservative but expected to be sufficiently accurate.

4. Results and discussion

The potential electrical energy, emission and cost savings that can be realised by installing VSDs on chillers, pumps and fans of mine cooling systems were estimated from all relevant data collected during the investigation, using Eqs. (1)–(10). Feasibility indicators were also calculated. Various loading and operational conditions were considered for different system groups to investigate viability and relevance to different decision makers.

A pilot study was also done by installing VSDs on the pumps of one site and evaluating the performance after 1 month. The key results are shown in support of the large-scale evaluation.

4.1. Chillers

Savings and feasibility factors were calculated when installing VSDs on all chiller compressor motors at various chiller thermal loading factors. The results for all the sites combined are given in Table 4. The first three columns show the savings that can be realised if chillers operate at various loading factor ranges. The last column shows the savings that can be realised if chillers typically continue running under the present average loading conditions.

An annual energy saving of 168,633 MW h, or 19.4% of the total chiller energy consumption, is possible for the typical operational loads of the chillers. This amounts to a reduction in CO_2 emissions of 153,590,958 kg/year and an annual cost saving of US$8,084,510. However, the costs of the medium-voltage VSDs that are required for chiller compressors are high in South Africa. The viability indicators are therefore high, with the payback period being 4.2 years and cost of conserved energy US$203/MW h.

Chiller savings and feasibility factors are shown to improve at lower loading factors. This is attributed to chiller compressor VSDs having more scope to modulate refrigerant flow rates than at high loading factors. 90–100% chiller thermal loading is shown to be particularly unfeasible for VSDs, with a payback period of 15.5 years.

It is clear that the large-scale introduction of VSDs to mine chillers will result in significant savings, but that it is not an economically feasible option. This is mainly as a result of high VSD costs and relatively high loading factors imposed on mine chillers by large and continuous mine cooling demands. It might be worthwhile to consider replacing selected oversized compressor motors by smaller energy efficient motors instead as this usually implies lower costs [61].

Table 5 shows the potential savings and feasibility factors when implementing VSDs on all the chillers of a typical mine cooling system with a combined cooling capacity of 40 MW. Mine energy managers can use these results as a guideline to the potential savings and drawbacks of chiller VSDs. An energy saving of 7013 MW h/year, or 19.1%, is possible for typical chiller operations.

Table 4
Chiller energy consumption, energy and emission savings and cost analysis (all sites combined).

	Chiller loading			
	50–70%	70–90%	90–100%	Typical operation
Energy consumption without VSD (MW h/year)	717,928	920,421	1,104,505	868,780
Energy consumption with VSD (MW h/year)	524,620	773,154	1,058,484	700,147
Energy saving (MW h/year)	193,288	147,267	46,021	168,633
CO_2 emission reduction (kg/year)	176,047,078	134,131,107	41,915,971	153,590,958
SO_2 emission reduction (kg/year)	1,403,670	1,069,463	334,207	1,224,622
NO_x emission reduction (kg/year)	741,690	565,097	176,593	647,082
Cost savings (US$/year)	9,266,525	7,060,210	2,206,315	8,084,510
Cost (US$)	34,209,375	34,209,375	34,209,375	34,209,375
Payback period (years)	3.7	4.8	15.5	4.2
Cost of conserved energy (US$/MW h)	177	232	743	203

Table 5
Chiller energy consumption, energy and emission savings and cost analysis (typical site with 40 MW combined chiller cooling capacity).

	Chiller loading			
	50–70%	70–90%	90–100%	Typical operation
Energy consumption without VSD (MW h/year)	31,943	41,136	48,987	36,736
Energy consumption with VSD (MW h/year)	24,234	35,281	47,314	29,723
Energy saving (MW h/year)	7709	5856	1673	7013
CO_2 emission reduction (kg/year)	7,021,604	5,333,199	1,523,359	6,387,241
SO_2 emission reduction (kg/year)	55,985	42,523	12,146	50,927
NO_x emission reduction (kg/year)	29,582	22,469	6,418	26,910
Cost savings (US$/year)	369,594	280,722	80,185	336,203
Cost (US$)	1,459,836	1,459,836	1,459,836	1,459,836
Payback period (years)	3.9	5.2	18.2	4.3
Cost of conserved energy (US$/MW h)	189	249	873	208

Table 6
Chiller energy consumption, energy and emission savings and cost analysis (typical chiller with 5 MW cooling capacity).

	Chiller loading			
	50–70%	70–90%	90–100%	Typical operation
Energy consumption without VSD (MW h/year)	4591	5886	7063	5259
Energy consumption with VSD (MW h/year)	3355	4944	6769	4140
Energy saving (MW h/year)	1236	942	294	1119
CO_2 emission reduction (kg/year)	1,125,794	857,748	268,046	1,018,797
SO_2 emission reduction (kg/year)	8976	6839	2137	8123
NO_x emission reduction (kg/year)	4743	3614	1129	4292
Cost savings (US$/year)	59,258	45,149	14,109	53,626
Cost (US$)	176,073	176,073	176,073	176,073
Payback period (years)	3.0	3.9	12.5	3.3
Cost of conserved energy (US$/MW h)	142	187	598	157

Table 7
Pump and fan energy consumption, energy and emission savings and cost analysis (all sites combined).

	Pump and fan speed reduction			
	10%	20%	30%	Typical operation
Energy consumption without VSD (MW h/year)	449,445	449,445	449,445	449,445
Energy consumption with VSD (MW h/year)	350,567	251,689	175,284	304,724
Energy saving (MW h/year)	98,878	197,756	274,161	144,721
CO_2 emission reduction (kg/year)	90,057,996	180,115,992	249,706,262	131,812,158
SO_2 emission reduction (kg/year)	718,057	1,436,113	1,990,975	1,050,974
NO_x emission reduction (kg/year)	379,416	758,833	1,052,018	555,328
Cost savings (US$/year)	4,740,349	9,480,699	13,143,696	6,938,148
Cost (US$)	9,798,394	9,798,394	9,798,394	9,798,394
Payback period (years)	2.1	1.0	0.7	1.4
Cost of conserved energy (US$/MW h)	99	49	36	68

This is equivalent to a site cost saving of US$336,203/year. However, the payback period of 4.3 years and cost of conserved energy of US$208/MW h indicates the impracticality of changing over to VSDs. Chiller VSDs are therefore only recommended on sites where chillers have low loading factors and where sufficient funds are available.

Table 6 shows the same savings and feasibility analysis for one chiller with a 5 MW cooling capacity. The typical operational results indicate an energy saving of 1119 MW h/year, or 21.3%, with a payback period of 3.3 years. These results are better than shown in Tables 4 and 5. This is because better relative improvements in COPs can be achieved when using VSDs on smaller chillers and the lower VSD costs associated with 6600 V chillers, as used in this example. Plant managers can therefore expect significant savings when implementing VSDs on selected chillers, especially smaller chillers with suitably low loading factors. However, initial capital outlay, cost-effectiveness and trade-offs with pump and fan VSDs must be carefully considered.

4.2. Pumps and fans

Savings and feasibility factors were calculated when installing VSDs on all pump and fan motors at various speed reductions. The results for all the sites combined are given in Table 7. The 10–30% speed reduction scenarios show the savings that can be realised if pumps and fans operate only at the given reduced speeds. The typical operation scenario shows the average savings that can be realised if pumps and fans operate at average daily part-load profiles to match the supply to the load demand. These partial loads differ from one site to another, but a typical example is the chilled water flow demand profile shown in Fig. 3.

An energy saving of 144,721 MW h/year, or 32.2% of the total pump and fan energy consumption, is shown to be possible for typical speed reduction profiles. This amounts to a reduction in CO_2 emissions of 131,812,158 kg/year and an annual cost saving of US$6,938,148. Viability indicators are low, with a payback period being 1.4 years and the cost of conserved energy US$68/MW h.

Table 8
Pump and fan energy consumption, energy and emission savings and cost analysis (typical site with 3.4 MW combined pump and fan installed capacity).

	Pump and fan speed reduction			
	10%	20%	30%	Typical operation
Energy consumption without VSD (MW h/year)	22,455	22,455	22,455	22,455
Energy consumption with VSD (MW h/year)	17,515	12,575	8758	15,225
Energy saving (MW h/year)	4940	9880	13,698	7231
CO_2 emission reduction (kg/year)	4,499,515	8,999,030	12,475,929	6,585,654
SO_2 emission reduction (kg/year)	35,876	71,752	99,474	52,509
NO_x emission reduction (kg/year)	18,957	37,913	52,561	27,746
Cost savings (US$/year)	236,839	473,679	656,691	346,647
Cost (US$)	460,754	460,754	460,754	460,754
Payback period (years)	1.9	1.0	0.7	1.3
Cost of conserved energy (US$/MW h)	93	47	34	64

The average payback period indicates feasibility since it is less than the suggested benchmark of 2 years.

These results are significantly better than those shown for chiller VSDs in Table 3. This is because relatively larger energy reductions can be achieved more easily by reducing pump and fan motor speeds. Furthermore, low-voltage VSDs incur lower costs. This is illustrated by the cost of conserved energy of pump and fan VSDs that is almost one third of the cost of conserved energy of chiller VSDs.

The typical daily part load profiles used for the typical operation condition take into account the various mine site water requirements, working schedules and storage dam capacities. It has been shown that a variable water flow strategy does not adversely affect performance or mine service delivery requirements [39].

Savings and payback periods improve with speed reduction and it is shown that 274,161 MW h/year, or 61%, can be saved with a payback period of 0.7 years for a constant speed reduction of 30%. It has been shown experimentally that chilled and cooling water flow reductions of this order do not reduce chiller COPs by more than 5% [20]. The pump savings of up to 61% are generally found to outweigh possible chiller COP reductions, depending on the installed capacities. However, reducing the chilled or cooling water flow by more than about 40% of design flow causes transition into the laminar flow region, reducing heat transfer rates and increasing water-side fouling. This usually results in automatic chiller shutdowns and a significant decrease in chiller COPs that outweigh pump benefits and impede viability [51,62]. Pump speed reductions of more than 30% have thus conservatively not been included in this investigation.

The additional savings that will be realised by opening flow control valves fully and maintaining design flows are difficult to quantify since it depends on the specific valve opening. This is expected to be significant and will increase the reported savings.

It is clear that it will be feasible to install VSDs on all low-voltage pumps and fans on mine cooling systems. Reported savings and payback periods are conservative but significant and indicate that this is a more rewarding option than chiller VSDs.

Table 8 shows the potential savings and feasibility factors when installing VSDs on all the pumps and fans of a typical mine cooling system with a combined pump and fan installed capacity of 3.4 MW. Mine energy managers can use these results as a guideline to the saving potential of pump and fan VSDs. An energy saving of 7231 MW h/year, or US$346,647/year, is possible for typical speed reductions. The low payback period of 1.3 years and cost of conserved energy of US$64/MW h indicates feasibility. Installing VSDs on all pumps and fans of a typical mine cooling system can therefore be recommended, especially if large speed reductions are possible or where existing electric motor specifications have been significantly overestimated.

Table 9 shows a savings and feasibility analysis for single 75 kW and 200 kW pump or fan VSDs.

Table 9
Pump and fan energy consumption, energy and emission savings and cost analysis (typical operation of a 75 kW and 200 kW pump or fan motor).

	Motor rating	
	75 kW	200 kW
Energy consumption without VSD (MW h/year)	497	1,325
Energy consumption with VSD (MW h/year)	337	898
Energy saving (MW h/year)	160	427
CO_2 emission reduction (kg/year)	145,700	388,534
SO_2 emission reduction (kg/year)	1162	3098
NO_x emission reduction (kg/year)	614	1637
Cost savings (US$/year)	7669	20,451
Cost (US$)	14,993	24,918
Payback period (years)	2.0	1.2
Cost of conserved energy (US$/MW h)	94	58

Typical operational results indicate energy savings of 160 MW h/year and 427 MW h/year, respectively. The payback period for a 75 kW unit is 2 years while it is only 1.2 years for a 200 kW unit. While both seem viable, the 200 kW VSD application is more feasible because of the reduced US$/kW values for larger drives. If plant managers want to implement VSDs on only selected pumps or fans and funding is available, it is recommended that they start with larger units, provided that sufficient speed reduction is possible.

4.3. Pilot implementation

VSDs were installed on 19 pumps of the South Deep gold mine surface cooling systems as a pilot study to experimentally evaluate energy savings. The key results can be used to validate the findings of the saving potential study discussed in the previous sections. Power ratings of the pump groups that were fitted with VSDs as well as the relevant costs are given in Table 10.

The electrical energy consumption of the various pumps was monitored over a period of 1 month after implementation. These results were then compared to the electrical energy consumption of the same pumps, over the same number of running hours, before VSD installation. As commonly done during measurement and verification, only running hours were compared for which operating conditions such as ambient conditions and service requirements were comparable [63]. The results for the different pumps motor sizes are shown in Fig. 4.

Fig. 4 shows that there was a clear reduction in energy consumption of all the pump motors. The 132 kW motors showed the greatest reduction in energy consumption because the largest number of VSDs was installed on these motors. The total site electrical energy saving after 1 month amounted to 250 MW h, or 29.9% of the baseline energy consumption. This correlates closely to the estimated 32.2% saving shown in Table 7 for the large-scale use of VSDs. CO_2 emission reductions amounted to 227,893 kg.

Table 10
Power ratings and costs of VSDs retrofitted to pumps at the South Deep mine surface cooling systems.

	Qty.	Individual power rating (kW)	Total cost (US$)
Chilled water (evaporator) pumps	4	55	42,370
	3	132	43,331
	1	200	20,117
Cooling water (condenser) pumps	4	132	57,775
	3	110	39,648
	1	200	20,117
Transfer water pumps	3	75	34,846
Total	19		258,203

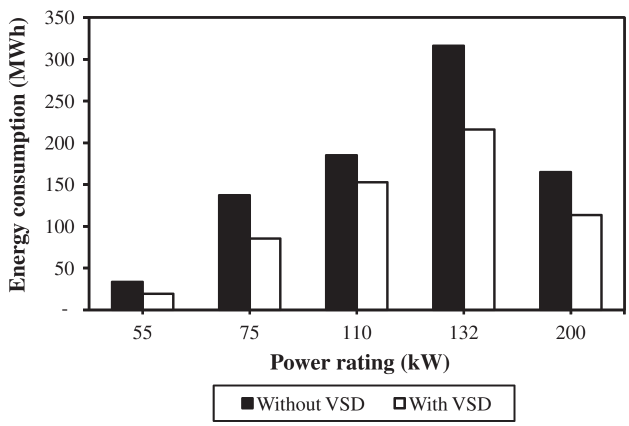

Fig. 4. Energy consumption of pump motor groups with different power ratings (1 month of pilot implementation).

The total cost savings for the month amounted to US$11,996. This implies a payback period of 1.8 years, indicating feasibility. However, the pumps were not operated continuously. It is worth noting that had this been the case, the cost savings would have been US$22,054 with a payback period of only 1 year. Increased VSD usage will therefore reduce the payback period and the cost of conserved energy. Also, the average future value of the savings is expected to be higher as a result of annual increases in electricity tariffs, depending on the expected life of the VSDs [56]. The reported savings for 1 month are therefore conservative.

The realised energy savings of the various types of pumps are shown in Fig. 5. It can be seen that the largest contribution to the savings was made by the chilled water pumps, realising 49% of the total savings. This was followed by the cooling and transfer water pumps with 30% and 21%, respectively. The major share of the chilled water pumps can be attributed to the drives that modulated the primary water flow rates in quick response to part load conditions and to the fact that the chilled water lines were throttled significantly by control valves before implementation. Cooling water VSDs generally took longer to modulate the secondary water flow relative to part load changes. Furthermore, these water supply lines were not throttled by valves before implementation.

Fig. 6 shows the average chilled water flow rate and electrical power input for full load conditions of one of the chilled water pumps. This shows the effect of replacing valve control with VSD control, even before any flow modulation takes place. While the design flow rate remained relatively constant, the electrical input power was reduced by 54%. Although the extent of this reduction depends on the extent of pump motor over-specification, the benefit of VSD control is clear.

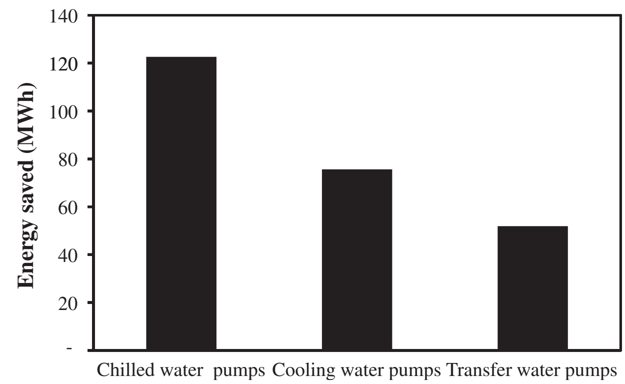

Fig. 5. Energy savings of chilled, cooling and transfer water pump motors (1 month of pilot implementation).

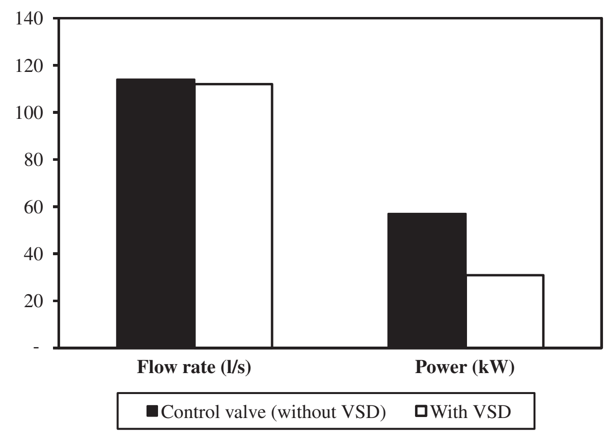

Fig. 6. Chilled water flow rate and pumping power when controlling flow with a control valve (without VSD) or with a VSD.

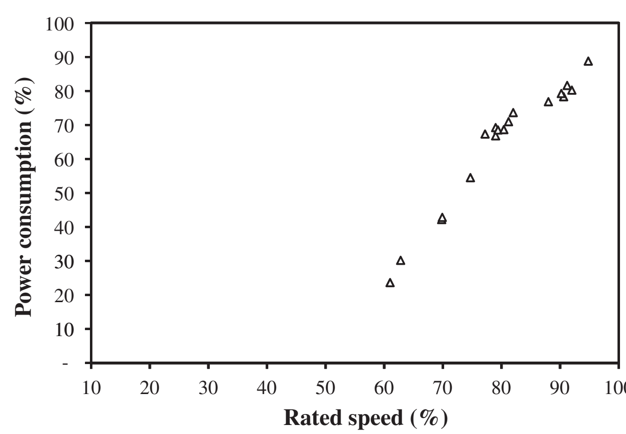

Fig. 7. Relationship between average motor power reduction and rated speed after VSD implementation (1 month of pilot implementation).

The average speeds and electrical power consumed by the various motors are shown as percentages in Fig. 7. It can be seen that the speed mostly varied between 75% and 95%. The general trend of the profile corresponds well to that shown in Fig. 1 [31]. The power reductions associated with different speed reductions estimated in the previous section are therefore realistic.

There were no adverse effects on the chilled water and ventilation air service delivery of the South Deep mine after VSD installation. No technical problems such as harmonic distortion and radio frequency interference were introduced. Preventative methods such as input and motor chokes and correctly shielded cables were applied. The benefits of VSDs also showed greater acceptance among plant personnel, especially after the actual energy savings were made available. These observations prove that technical and awareness concerns should not prevent the implementation of VSDs on mine cooling systems.

5. Conclusions

There is a global and South African drive for industrial energy efficiency improvement and GHG emission reduction. Large cooling systems on South African mines were identified to have the potential for significant energy efficient improvements by the large-scale introduction of VSD technology. An overview of VSD state-of-the-art highlighted its energy saving potential, especially when applied to chillers, pumps and fans. A summary of VSD costs in South Africa was given and the potential barriers to large-scale applications were discussed.

Mine cooling systems were reviewed and the results of an energy audit on 20 mine systems were presented. It was shown that the electrical energy consumption of these systems amounts to 1,318,225 MW h/year, or 4% of the total electricity supplied to all mines. Chillers account for 66% of this energy consumption while pumps and fans account for 34%.

Potential electrical energy savings, cost savings, emission reductions and feasibility indicators were calculated for various situations when implementing VSDs on the chiller compressors, pumps and fans of the evaluated cooling systems. The following conclusions can be drawn from the results that were obtained:

– An electrical energy saving of 168,633 MW h/year (19.4%), cost saving of US$8,084,510/year and CO_2 emission reduction of 153,590,958 kg/year will be realised if VSDs are implemented on all chiller compressor motors evaluated. However, the payback period of 4.2 years indicates that chiller VSDs are not a cost-effective option for widespread use on mine cooling systems. Investigating the replacement of selected oversized chiller motors with energy efficiency motors is recommended instead.
– It may be viable for mine energy managers to consider chiller VSDs for smaller chillers (below 6 MW cooling capacity), especially when the chillers are operating at low loading factors and if sufficient funds are available.
– An electrical energy saving of 144,721 MW h/year, or 32.2%, cost saving of US$6,938,148/year and CO_2 emission reduction of 131,812,158 kg/year will be realised if VSDs are implemented on all pump and fan motors evaluated. The payback period of 1.4 years indicates that pump and fan VSDs are cost-effective options for widespread use on mine cooling systems.
– Pump and fan VSDs can be recommended for most mine cooling systems, especially in cases where large speed reductions are possible and where motors are significantly oversized. In cases where only a limited number of pumps can be retrofitted with VSDs, it is more cost-effective to consider larger motors first.

VSDs were installed on pumps of the South Deep gold mine surface cooling systems as a pilot study to support the generalised findings. The following conclusions can be drawn from the results from 1 month:

– An electrical energy saving of 250 MW h, or 29.9%, cost saving of US$11,996 and emission reduction of 227,893 kg were realised. The payback period of 1.8 years indicates feasibility and it was shown that this can be reduced to 1 year if pumps are operated for longer periods. These results support and validate the general estimates made for large-scale VSD usage.
– Chilled water pumps realised 49% of the total energy savings. This was largely as a result of the significant improvement when replacing valve flow control with VSD flow control on the specific cooling system.
– No adverse effects such as harmonic distortion, radio frequency interference or reduction in service delivery requirements were introduced by the VSD installations.
– It can be concluded that there is a definite potential benefit, both financial and in energy efficiency, for the large-scale use of VSD technology on mine cooling systems in South Africa. It is recommended that decision and policy makers seriously consider VSDs implementation on pumps and fans of these systems. The potential impact on mine cooling systems is significant and it will contribute considerably to the improvement of South African and global industrial energy efficiency and sustainability.

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Annexure A.2

***Applied Energy* (2013) journal information and editorial requirements**

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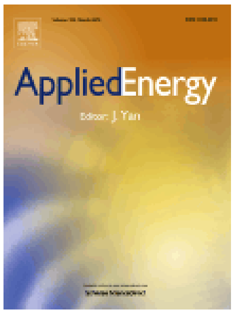

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Annexure B.1

The development and integrated simulation of a variable water flow energy saving strategy for deep-mine cooling systems

- G.E. du Plessis, D.C. Arndt, E.H. Mathews

- Submitted to *Energy*

This article focuses on the proposed variable-flow strategy and the adapted simulation model to predict its energy saving proposal. This follows in response to the findings of the shown potential for VSDs in the previous article. Simulation results of the Kusasalethu case study are presented. The article therefore complements Chapters 4 and 6. The article is still in review and is therefore presented in the format submitted to the journal.

THE DEVELOPMENT AND INTEGRATED SIMULATION OF A VARIABLE WATER FLOW ENERGY SAVING STRATEGY FOR DEEP-MINE COOLING SYSTEMS

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ABSTRACT

Increasing the energy efficiency of deep level mine cooling systems is an important method to improve the sustainability of the mining industry. Cooling systems consume up to 25% of the total electricity used on deep mines. These systems are integrated with the water reticulation system to provide chilled service water to the mine and provide cool ventilation air. A new energy efficiency strategy, based on variable water flow, was developed for the unique demands of an integrated mine cooling system. The strategy is based on procedures such as matching the evaporator thermal requirements to the demand for chilled water, adapting the condensers to the heat load, and matching the bulk air cooler with the demand of ventilation air requirements. A suitable simulation model of integrated mine cooling systems was developed, verified and used to predict the potential results of implementing the new strategy on actual mine systems. In this paper, an overview of the developed strategy and simulation model is presented. The verified simulations show that a decrease of 33% in overall electrical energy consumption is possible by implementing the proposed energy saving intervention.

KEYWORDS

Deep mines

Electrical demand-side management

Cooling system energy efficiency

Integrated simulation model

Variable water flow

NOMENCLATURE

A	flow admittance	(m^4)
C	average heat capacity rate	(W/ºC)
COP	coefficient of performance	(-)
c_p	specific heat at constant pressure	(J/kg.ºC)
e	control error	(-)
e_i	time-integrated control error	(-)
h	specific enthalpy	(J/kg)
k_p	proportional gain constant	(-)
k_i	integral gain constant	(-)
$\dot{m}$	mass flow rate	(kg/s)
o	control output	(-)
Δp	pressure difference	(Pa)
PL	partial cooling load factor	(-)
$\dot{Q}_e$	cooling capacity	(W)
r	capacity ratio, defined by Eq. (5)	(-)
T	temperature	(ºC)
UA	overall heat transfer coefficient *x* area	(W/ºC)
$\dot{W}_c$	compressor input power	(W)
$\dot{W}_p$	pump input power	(W)

GREEK SYMBOLS

η	pump and motor efficiency	(-)
ρ	density	(kg/m³)
τ	heat exchanger effectiveness, defined by Eq. (4)	(-)
φ	water saturation enthalpy - water temperature ratio	(J/kg.ºC)

SUBSCRIPTS

a	air
avg	average between inlet and outlet conditions
c	condenser
e	evaporator
i	inlet
o	outlet
p	pump
r	refrigerant
ref	reference design condition
sat	saturated water vapour
w	water

1. BACKGROUND

There are global concerns regarding sustainability in various industries. Increasing energy demands need to be suitably managed while taking into account the associated environmental, economic and sustainability factors. Industrial and mining sectors consume about 37% of the world's total delivered energy [1]. South African mines use approximately 15% of the national electricity supply [2]. In South Africa, mining is therefore a sector in which it is important to consider demand-side management as a viable option for sustainable production. This will also improve the reserve electricity power supply of the country's main electricity supply utility, Eskom [3].

Mine cooling systems consume up to a quarter of total mine electricity usage [4]. These systems are integrated with mine water reticulation systems to supply chilled water and maintain safe underground working and climatic conditions [5]. Deep level mines have virgin rock temperatures of up to 60ºC [6] and require underground wet-bulb temperatures of between 26.5ºC and 28.5ºC [7]. Cooling demands are high and increase with the increasing mining depths and changing global surface climatic conditions. Reducing the energy usage and operating costs of deep-mine cooling systems is thus an important demand-side management incentive.

Efficient control methods for existing systems have recently been developed and successfully implemented [8]. However, energy efficient strategies that require modern control technologies, specifically catering for integrated operation and service delivery demands of mine cooling systems, need further development.

This paper reports on the development and simulation of a new energy efficient intervention for deep-mine cooling systems. The strategy involves the optimal control of water flow through the various components of the system while taking into account the additional constraints imposed by the integrated system. An integrated control and energy management system is developed and proposed to implement the strategy on deep level mines. A simulation model of the integrated mine cooling system is developed, verified and utilised to predict the potential savings that can be realised on various deep-mine cooling systems. The key results of implementation on one site are also given. The main objective is to show the potential impact of the simulated strategy on mine cooling systems in broad terms. Emphasis will therefore be on the description of the developed energy management solution, the simulation model and the potential energy- and cost-saving benefits for various mine cooling systems rather than on detailed implementation results and the effects thereof.

2. MINE COOLING SYSTEMS

2.1 LAYOUT AND OPERATION

A deep-mine cooling system forms an important part of the integrated mine water reticulation system. Chilled water, usually at a temperature of about 5ºC, is supplied by a surface cooling system to a network of underground storage dams or other cooling plants from where it is used for a variety of purposes. These include cooling of machines used in operations [9], underground local air cooling operations such as spot coolers as well as bulk ventilation air cooling to comply with acceptable wet-bulb temperatures of South African mines [7]. After use, the water is stored in various underground hot water dams, typically 32ºC, before being pumped back to the surface cooling system.

A typical layout of a deep-mine surface cooling system is shown in Fig. 1. Hot water is pumped from underground into a surface hot water storage dam. It is then fed through pre-cooling towers into a pre-cooling dam. From here the water is pumped through and cooled in the evaporators of an arrangement of refrigeration plants. A heat-exchange condenser water circuit expels the heat by means of condenser cooling towers. The chilled water is stored in a chilled water dam from where it is sent underground when required.

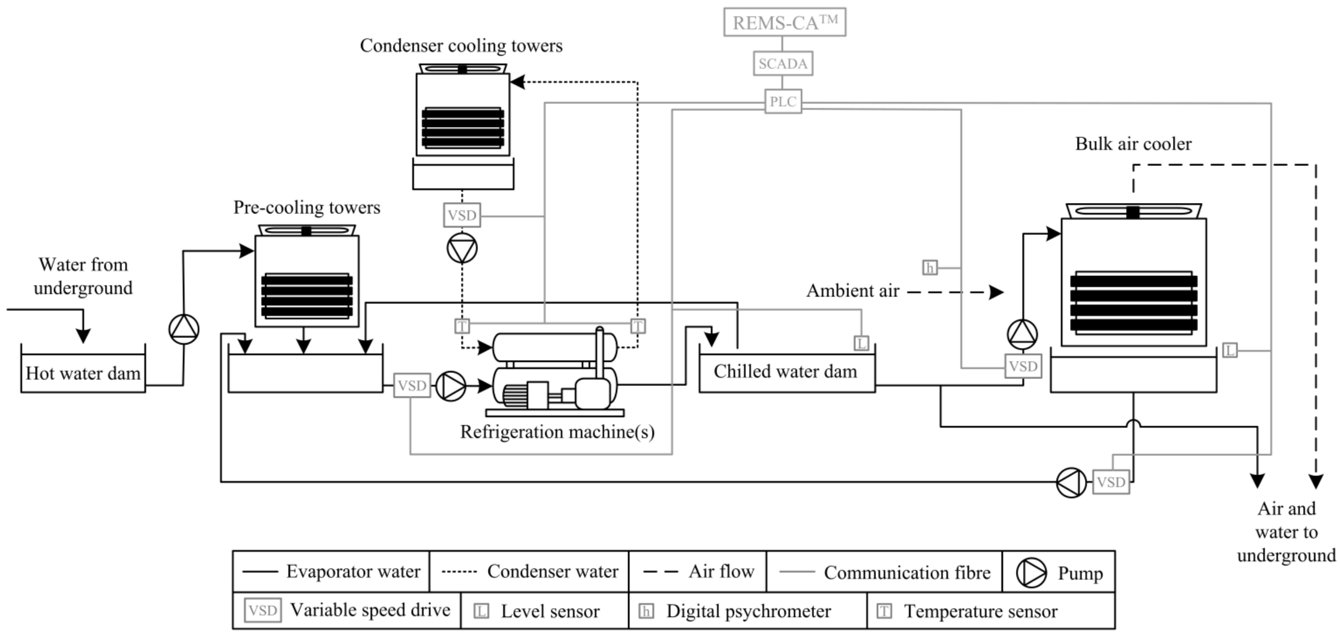

Fig. 1. A typical deep-mine cooling system layout (shown with the addition of the developed energy saving strategy and the REMS-CA™ system)

Chilled water is also used to cool ambient air in a bulk air cooler (BAC). The cooled air is used for mine ventilation and the used water returned to the pre-cooling dam. Water from the chilled water dam may be recycled into the pre-cooling dam when necessary.

Refrigeration machines typically use R134a or ammonia and have individual cooling capacities of up to 20 MW. Centrifugal and screw compressors are most commonly used in these plants. Cooling loads are controlled by means of guide vanes in centrifugal compressors and slide valves in screw compressors [10]. These control methods adjust the refrigerant flow rate and hence the cooling capacity to ensure that a set evaporator outlet water temperature is maintained for variable inlet conditions [11].

The purpose of the hot and chilled water dams is to provide storage capacity in the system [5]. This ensures that peak water demands can be met while, simultaneously, catering for the fluctuation in water flow requirements. Major variations in cooling requirements resulting from seasonal changes are allowed for by varying the number of active refrigeration machines [12, 13]. This applies to the requirements of both bulk air cooling and service water.

A typical deep-mine cooling system operates at a predetermined design point water flow rate through the refrigeration machines. These flow rates are usually regulated by using a variable opening control valve. When the chilled water dam is full, the water is returned to the pre-cooling dam until the chilled water is required underground or for bulk air cooling. It is also not unusual 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.

The supply of sufficient water at a specified temperature is easily achieved by existing operational and control components of deep-mine cooling systems. However, the supply often exceeds the demand without taking into account optimal and energy efficient equipment operations. An energy-conscious awareness is necessary since a continuous review is required if the changing needs of the mining industry are to be met [14].

2.2 ENERGY SAVING CONSIDERATIONS

An energy saving strategy which has been successfully implemented on some mine cooling systems reduces the evaporator water inlet temperature by recycling chilled water back to the pre-cooling dam. This decreases the constant water flow cooling load [8]. Although effective, this strategy has limitations in that only existing infrastructure is used and hence the saving potential from varying pump or compressor loads is not realised. Indirect cooling energy savings have also been achieved by methods that focus on reducing water demand in underground water reticulation systems [14, 15]. The actual cooling energy savings of these methods have not been quantified.

Variable speed technology has long been considered a standard energy efficient method to enhance the energy performance of chiller systems [16]. This is particularly applicable 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 variable speed drives (VSDs) on cooling compressors to optimise operating speed at part-load conditions [17, 18]. This applies to load-based speed control of cooling tower fans, evaporator and condenser water pumps as well [16, 19].

The development of a mine cooling system energy savings strategy based on existing variable water flow methods has shown 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 [20]. It is therefore important that the strategy is specifically developed taking the unique deep-mine cooling as well as operational and safety requirements into account.

3. ENERGY SAVING STRATEGY

Energy saving components identified for deep-mine cooling systems are the evaporator, condenser and BAC water flow control. Various methods can be used to alter the water flow rate. These include VSDs to control the pump rotational speed and automatically actuated control valves, as shown in Fig. 1. Water temperature and dam level sensors as well as a compact digital psychrometer are also required. All instrumentation and control communications are typically coupled with the existing programmable logic controllers (PLCs).

3.1 EVAPORATOR WATER FLOW CONTROL

The constraints placed on the evaporator water line are the requirements for a specific cold water temperature that will be available in the chilled water dam on demand.

Manually operated variable opening valves are usually used to obtain the required flow. These valves must be in the full open position to reduce pressure losses. The water pump speeds will be reduced by the VSDs to obtain the design flow. This alone presents a base energy saving as a result of the cubic flow power relation [21].

Recycling of chilled water dam overflow to the pre-cooling dam can be eliminated by controlling the dam level to remain below 100%. This enables the water flow rate to be reduced below design conditions during times of low demand. The average evaporator water inlet temperature increases because no recycled chilled water is available to lower the average pre-cooling dam temperature. Because the compressor guide vanes maintain a fixed water outlet temperature the water temperature difference across the heat exchanger increases [11]. The ideal heat exchange in the evaporator [5] is given by Eq. (1).

$$\dot{Q}_e = \dot{m}_w c_{pw}(T_{wi} - T_{wo}) = \dot{m}_r \Delta h_r \quad (1)$$

It follows that the water flow can be reduced and pump savings realised without adversely affecting the refrigeration load.

The water flow rate through the evaporator will be controlled by means of a proportional-integral (PI) control loop using the desired chilled water dam level as set point. This ensures that the requirements of available chilled water are met while decreasing water pump and compressor energy consumption at both the design point and reduced loads. Furthermore, the water flow rate is not to be decreased below about 60% of the design flow speed because transition into the laminar flow region occurs, reducing heat transfer and increasing water-side fouling. This results in a decrease of the plant coefficient of performance (COP) [22].

3.2 CONDENSER WATER FLOW CONTROL

The constraints on the condenser water flow are the condenser cooling tower limitations and the cooling load. However, the effects of varying condenser water flow must be carefully considered. Most manufacturers warn against simply decreasing the water flow since the rejected heat remains constant and therefore the condenser temperature difference across the condenser will increase. This results in an increased compressor discharge pressure which increases energy usage and lowers the COP at partial load conditions [11].

The preferred strategy is therefore to adapt to the changing chiller load by maintaining the design condenser temperature difference when varying the water flow, as recommended [16]. Condenser water pumps on mine installations are generally driven by high powered electric motors, resulting in the water pump savings outweighing minor reductions in machine performance.

The water flow rate of the condenser water is to be controlled by means of a PI control loop using the required water temperature difference as set point. In addition to water pump savings at partial load conditions, full-load savings are also expected by reduced pump rotational speeds when the variable opening control valves are opened fully.

3.3 BULK AIR COOLER WATER FLOW CONTROL

Surface BACs are typically direct contact-type heat exchangers that cool ambient air through spray chambers. The wet-bulb temperature of the cool ventilation air entering the shaft is usually about 8ºC. This will usually ensure and maintain the maximum underground wet-bulb temperature at or below 27.5ºC [15]. This defines the main constraint when developing a variable BAC flow strategy. Off-design ambient conditions are more commonly encountered and typical BAC operations supply ventilation air at wet-bulb temperatures much lower than required.

The key factors which influence the heat exchange efficiency in BACs are the ambient air flow, temperature and humidity, the inlet water flow and temperature and the BAC design [5]. If the air flow is kept constant, the only parameter that can be directly controlled is the water flow. The proposed control strategy is to vary the BAC supply water flow rate (by means of VSDs or control valves) according to the ambient conditions in order to meet the mine ventilation air demands.

Although this also results in water pump savings when VSDs are used, the primary saving comes from the reduction in chilled water demand. The extent of the saving depends on ambient conditions, but significant reductions are expected in the daily amount of water to be chilled.

A feed-forward control strategy controls the flow rate by using ambient enthalpy as input. The air enthalpy is calculated in real-time, using air pressure and wet- and dry-bulb temperatures, obtained from a compact digital psychrometer. An air enthalpy increase, at a constant dry-bulb temperature, signifies an increase in relative humidity [5]. More water flow is required and the valves will be commanded to open proportionally. When the enthalpy decreases the reverse process takes place.

3.4 ADDITIONAL CONSIDERATIONS

Some additional measures that are specific to each installation site might need to be considered in order to implement the described strategies optimally. These may include, but are not limited to, the replacement or cleaning of old cooling towers and installing VSDs on return water pump systems in order to control dam level capacities. The inclusion of such measures would be based on cost-effectiveness and their contribution to the efficient operation of the developed variable flow strategies.

3.5 INTEGRATION

There is a strong relation between energy efficiency and control systems when considering them in terms of performance, operation, equipment and technology [23]. This is expected since the high level objectives of an energy efficiency strategy are usually required to be realised by the objectives of a lower level control system. It follows that it is necessary to utilise a suitable control and energy management system to integrate and implement the developed energy saving strategies.

It has been shown that optimised system control should occur as close as possible to real-time to react to system disturbances and enable maximum energy savings [24]. The importance of transforming and simplifying complex modelling and control problems such as the global optimisation of cooling systems has also been demonstrated [25]. An effective controller should therefore be simple, robust and practical.

Mine ventilation control systems have been investigated by Hu et al. [26], Koroleva et al. [27] and McPherson et al. [28]. With regards to the requirements mentioned previously, the shortcomings of these models are that they are complex and do not include the control of integrated cooling systems of mine ventilation networks. The optimal control of variable speed pumps in HVAC systems were reported by Tillack and Rishel [29] and Green [30]. However, the system requirements of large cooling systems on mines differ sufficiently that these models cannot simply be adjusted to suit mine system needs.

In order to implement, control, monitor and report on the outlined strategies for mine cooling systems, new energy management software called Real-time Energy Management System for Cooling Auxiliaries^{TM} (REMS-CA^{TM}) was developed [31]. REMS-CA^{TM} communicates with the mine's supervisory control and data acquisition (SCADA) system via the object linking and embedding (OLE) for process control (OPC) standard. The SCADA system communicates with all plant PLCs and is used for monitoring and control of all mine systems. REMS-CA^{TM} therefore operates interactively by retrieving relevant plant parameters (such as temperatures, dam levels and flow rates) and controlling relevant plant parameters such as drive frequencies.

REMS-CA™ takes over total automatic control of the installed infrastructure by implementing the outlined energy saving strategies in real-time. The required control set points such as dam volume levels, condenser temperature differences and control valve limits are defined by the user. Feedback from the plant parameters is continuously updated and the optimal operation of the integrated system calculated.

Additional considerations in REMS-CA™ include failsafe set points, minimum controllable standards and safety requirements of the specific mine. Furthermore, energy savings realised by the automated energy-efficient measures are monitored and automatically reported in detail on a daily basis. To quantify savings, principles in *The Measurement and Verification Guideline for Energy Efficiency and Demand-Side Management (EEDSM) Projects and Programmes* published by electricity utility Eskom’s Corporate Services Division Assurance and Forensic Department, are adopted [32].

4. SIMULATION MODEL

4.1 OVERVIEW

The developed energy saving strategy must be simulated in order to evaluate its potential energy and cost savings. Although the performance of mine chillers have previously been simulated [12], no commercially available packages exist that simulate integrated mine cooling systems.

An integrated, dynamic, component-based simulation model was developed which balances energy and mass over defined time intervals. Provision was made for hourly inputs over a period of 365 days, or 1 year, in order to reflect daily and seasonal changes in system boundaries.

Inputs are provided in the form of hourly ambient conditions, hourly mine demands of chilled water and system parameters such as dam capacities, cooling machine, BAC, pre-cooling tower, condenser cooling tower, water pump and PI controller specifications. Output of the simulation is given as the performance of the integrated system, including the combined power usage.

The mathematical models, based on thermodynamic and physical properties of the system, used in the simulation [33] are summarised below.

Direct contact heat exchangers (pre-cooling towers, condenser cooling towers and BACs):

$$h_{ao} = \frac{(1-r)}{(\tau - r)} h_{ai} + \frac{(\tau - 1)}{(\tau - r)} \varphi T_{wi} \tag{2}$$

$$T_{wo} = \frac{r(\tau - 1) h_{ai}}{(\tau - r)\varphi} + \frac{\tau(1-r)}{(\tau - r)} T_{wi} \tag{3}$$

$$\tau = \exp\left\{ -UA\left(\frac{\varphi}{c_{pw}\dot{m}_w} - \frac{1}{\dot{m}_a} \right) \right\} \tag{4}$$

$$r = \frac{\dot{m}_a \varphi}{c_{pw}\dot{m}_w} \tag{5}$$

$$\varphi = \frac{h_{sat,wavg}}{T_{wavg}} \tag{6}$$

Refrigeration machines:

$$\dot{Q}_e = \dot{Q}_{e,ref}\left((T_e - T_{e,ref})(C_e) + 1 \right)\left((T_{c,ref} - T_c)(C_c) + 1 \right) \tag{7}$$

$$COP = COP_{ref} \frac{\dot{Q}_e}{\dot{Q}_{e,ref}} \left(-0.781PL^2 + 1.25PL + 0.5313 \right) \quad (8)$$

$$\dot{W}_c = \frac{\dot{Q}_e}{COP} \quad (9)$$

Pumps:

$$\Delta p_p = \frac{\dot{m}_w^{\ 2}}{\rho_w A} \quad (10)$$

$$\dot{W}_p = \frac{\Delta p_p \dot{m}_w}{\rho_w \eta} \quad (11)$$

PI controllers:

$$o = ek_p + e_i k_i \quad (12)$$

Water and ambient macroscopic property restrictions, thermal capacitance dams and flow convergences were also modelled in order to configure flow networks and integrate components.

4.2 VERIFICATION

To verify the accuracy and viability of the developed simulation model, the baseline performance of an actual mine surface cooling system (Mine A) was simulated using historic data as input (before any energy saving interventions). Simulation results were then compared to the actual performance over the same period, which was during a summer month. The cooling system layout is similar to the general arrangement shown in Fig. 1, utilising 4 refrigeration machines and 3 gravity-fed BACs.

The average daily profile of the simulated and actual electrical power usage of the combined cooling system for the summer month under consideration is shown in Fig. 2. It can be seen that the simulation closely follows the actual power profile with an average accuracy of 4.1%. The verification process was repeated for 12 months of the year and an overall average accuracy of 7% was achieved. Given that the design, operation and schedules of the actual system are the same as used in the simulation, the model can be assumed to predict the overall system energy performance with an acceptable level of accuracy. The developed simulation model can therefore be used as a viable tool to investigate the energy saving potential of the develop strategies on deep-mine cooling systems.

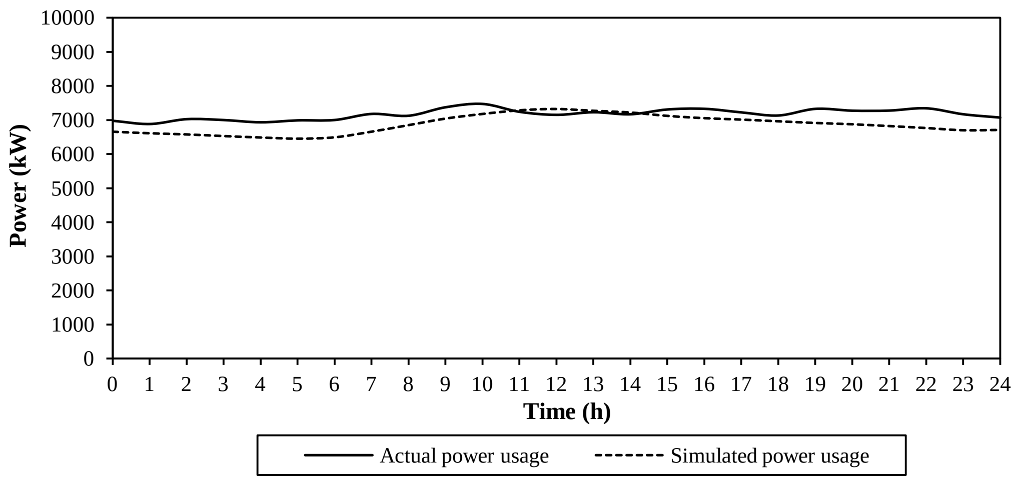

Fig. 2. Average daily profile of simulated and actual cooling system power usage for Mine A (one summer month)

4.3 ENERGY SAVING PREDICTIONS

The simulation model was used to calculate the potential savings that could be realised from the newly-developed strategy. Firstly, the same mine cooling system (at Mine A) and time period used for simulation verification was considered. Secondly, five other cooling systems (at Mines B – F) were simulated to investigate the wider potential of the strategy.

The equipment proposed for the cooling system on Mine A include 3 evaporator VSDs, 3 condenser VSDs, 2 BAC supply water valves, 3 BAC return water VSDs, and the replacement of old pre-cooling towers to enable the full saving potential of the variable water flow strategies to be realised. The control strategies are as described previously and integrated by REMS-CA™.

In order to simulate the application of the new strategy on Mine A, the demand requirements remained unchanged. The simulated electrical power usage in Fig. 2 was used as a baseline since this presents the simulated operation of the system before implementation of the energy saving strategy. The main system parameters used as input in the simulation are given in Table 1.

Table 1 Summary of input data used in simulation model prediction of energy savings (Mine A)

	Summer	**Winter**
Average hot water flow from underground (kg/s)	305	280
Average hot water temperature from underground (ºC)	28	28
Average chilled water to underground (kg/s)	305	280
Pre-cooling pump schedules	3 pumps full-time	3 pumps full-time
Evaporator pump operation	PI control to maintain chilled water dam level at 95%	
Condenser pump operation	PI control to maintain condenser water temperature rise at 5ºC	
BAC return pump operation	Forward loop control according to ambient enthalpy (25 – 70 kJ/kg)	
Pre-cooling towers in operation	8	8
Refrigeration machines in operation	4	2
Condenser cooling towers in operation	4	4
BACs in operation	3	0

New pre-cooling tower specifications:	
Inlet water temperature (ºC)	30
Outlet water temperature (ºC)	23
Inlet air wet-bulb temperature (ºC)	20

The simulated power usage profile before and after proposed implementation of the strategies on Mine A are shown for one summer month in Fig. 3. It is shown that there is significant potential to decrease the overall daily cooling system power usage by an average of 1509 kW, or 22%, during the summer month under consideration.

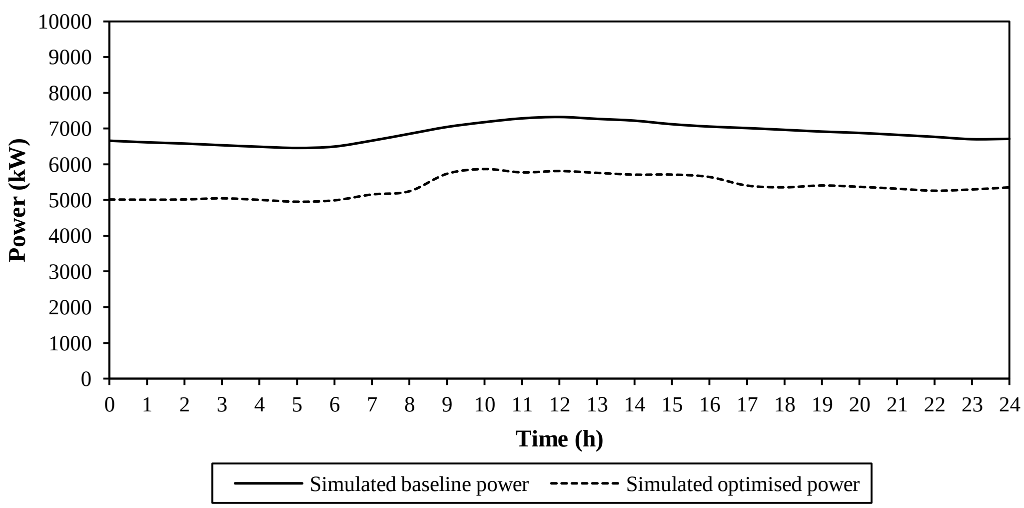

Fig. 3. Average daily profile of simulated cooling system power usage for Mine A (one summer month)

Table 2 shows the overall results when applying the simulation to all summer and winter months. It is shown that an annual average energy efficiency of 33% is predicted for Mine A. This will realise an annual cost saving of R4,880,346 (US$602,500 based on present exchange rates) or 23% of the yearly operating costs. The estimated installation cost is R5,241,322 which results in a payback period of 13 months. This indicates the economic viability of the developed strategy at Mine A.

Table 2 Simulated electrical energy savings for the cooling system of Mine A (monthly averages)

Month	**Baseline power (kW)**	**Optimised power (kW)**	**Total savings (kW)**	**Total savings (%)**
January	6965	5424	1541	22
February	6870	5361	1509	22
March	6334	4533	1801	28
April	5615	3551	2064	37
May	5175	3170	2005	39
June	3586	2144	1442	40
July	3430	1871	1559	45
August	3542	2088	1454	41
September	5196	3180	2016	39
October	5802	3747	2055	35
November	5868	3811	2057	35
December	6411	4567	1844	29
Average	**5399**	**3621**	**1779**	**33**

Most deep level mines have cooling systems similar in operation and service requirements to the system of Mine A. System layouts and specifications are slightly different and therefore the strategy details such as VSD sizes and control limits will change accordingly. The basic strategy principles and the integration thereof by means of REMS-CA^{TM} remain the same however. Further saving potential of the developed strategies was investigated for 5 other mine cooling systems. A summary of the overall results is given in Table 3.

Table 3 Simulated electrical energy savings for the cooling systems of Mines A – F (“R” = South African Rand; R1 = US$0.123)

	Combined cooling capacity (kW)	**Baseline (kW)**	**Energy saving (%)**	**Cost saving (R)**	**Payback period (months)**
Mine A	42,000	5,399	33	4,880,346	13
Mine B	39,000	5,700	25	4,681,243	8
Mine C	50,000	7,030	18	4,501,536	10
Mine D	46,000	7,070	21	4,413,889	8
Mine E	25,500	5,080	23	3,967,912	7
Mine F	40,000	8,880	14	3,690,742	10

Table 3 shows that the cooling capacities and average annual baseline power of the selected cooling systems are all comparable to Mine A. The simulated average energy savings that would result from implementing the developed strategies vary between 14% and 25% while the annual electricity cost savings are all above R3,500,000. The payback periods are all shown to be less than 13 months. The verified simulation model therefore indicates that the newly developed energy saving strategies show the potential to realise significant energy and cost savings on a variety of deep-mine cooling systems.

4.4. EXPERIMENTAL VALIDATION

The feasibility of the developed energy saving strategy is experimentally validated in detail elsewhere [34]. A case study was presented in which the effects of the strategies developed and simulated in this paper were evaluated with regards to the energy performance, service delivery and system performance of the cooling system of Mine A.

After one month of post-implementation performance assessment, the actual energy savings were shown to be 31.5% of the baseline power usage. This is accurate to within 4.5% of the simulated results presented in this paper. Service delivery was not notably affected since chilled water temperature and volume levels as well as ventilation air psychrometric conditions remained within acceptable limits. System performance was also not shown to be compromised since refrigeration machine coefficients of performance (COPs) and cooling tower, pump and electrical system performance parameters remained within acceptable limits.

Although the focus of this paper is on the actual strategies and the simulation model, the experimental results presented by Du Plessis et al. [34] highlight two key points. First, the variable water flow strategy and energy management system proposed and described here is further validated as a feasible new initiative to reduce the electrical energy usage of deep-mine cooling systems. Second, the suitability of the described simulation model as a predictive tool in energy saving investigations on deep-mine cooling systems is proven. The simulation can therefore be used confidently to evaluate the energy efficiency potential of various mine cooling systems.

5. CONCLUSIONS

Decreasing the electrical energy usage of deep-mine cooling systems is an important demand-side management initiative. It is essential that more attention be paid to optimised cooling load control and energy management, specifically in the mine cooling context that has been previously neglected to a large extent.

A new energy saving strategy based on variable water flow controlled by REMS-CA™ was developed for mine cooling systems. The strategy allows the supply of chilled water and ventilation air to be accurately matched to the demand through real-time control of the water flow through the evaporators, condensers and BACs of the integrated mine cooling system.

A simulation model of integrated mine cooling systems was developed and verified to predict the electrical energy saving results of implementing the new strategy on actual mine systems. The model is component-based and uses mine system constraints to predict integrated system performance profiles. The potential to reduce the total electrical energy consumption of the cooling system of a specific mine by an annual average of 33% was shown by simulation. Potential savings at five other cooling systems were also presented. It was shown that all considered cooling systems indicate the potential for cost-effective savings to be realised by the proposed energy saving strategy.

The viability of the strategy and simulation was further validated by considering experimental results. It was shown that the simulated energy savings of a specific cooling system were accurate to within 4.5% of actual energy savings of the same system.

The results presented indicate significant potential of the newly developed demand-side management incentive and simulation model for deep-mine cooling systems. The use of the simulation model and the application of the strategies will result in energy efficiency increases of cooling systems, contributing towards a more sustainable mining industry.

ACKNOWLEDGEMENTS

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Annexure B.2

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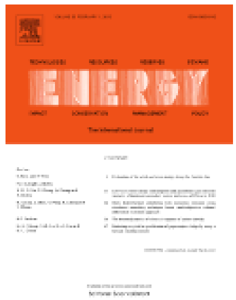

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Annexure C.1

A versatile energy management system for large integrated cooling systems

- G.E. du Plessis, L. Liebenberg, E.H. Mathews, J.N. Du Plessis

- Energy Conversion and Management, 2013

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This article focuses on the energy management system that was developed to implement and integrate the variable water flow strategy. The functionality of the system is discussed as well as selected case study results from Kusasalethu (parallel-series chiller system), Kopanang (parallel chiller system), South Deep South Shaft (cascade dam system) and South Deep Twin Shaft (BAC system). The expansion potential to other cooling systems is also discussed. It therefore complements Chapters 5, 7, 8 and 9.

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A versatile energy management system for large integrated cooling systems

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ABSTRACT

Large, energy intensive cooling systems are found on deep level mines to supply chilled service water and cool ventilation air to the mine. The need exists for a simple, real-time energy management tool for large, integrated cooling systems. A versatile energy management system was developed for the large cooling systems of deep mines as a typical example of a generic systems-based energy management tool. The system connects to the SCADA systems of mines and features a hierarchical control function. Set points of various subsystems are optimised in real-time by means of an integrated, systems approach. Real-time monitoring and automatic reporting functions support integrated energy management. In this paper, the development and viability of the system as a practical and versatile energy management platform are presented. *In situ* experimental results from implementation on four large cooling systems of different designs, sizes and requirements are considered to investigate the potential for such energy management tools. An average electrical energy saving of 33.3% is realised for all the sites without adversely affecting mine cooling requirements. The potential for application to other large cooling systems is also shown.

1. Introduction

Sustainable energy systems are priorities in policies of many countries [1]. The International Energy Agency (IEA) has shown that demand-side management (DSM) is more cost-effective than conventional supply-side policies [2]. Effective energy management largely depends on the type of industry [3]. It has been shown that a major general application area of DSM is cooling systems [4].

Cooling and ventilation is a field that is 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 [5] and in which various load management efforts have been made. This is particularly true for the building sector [6].

Building energy management systems (BEMSs) have gained popularity in contributing to continuous energy management of active building systems such as heating, ventilation and air-conditioning (HVAC) systems [7]. BEMS systems have also been extended to interact with renewable energy systems [8,9]. Considerable research efforts have been made in recent years to add advanced control methods to BEMS systems. These include fuzzy control [10], genetic algorithms [11], neural networks [12], evolutionary programming [13] and online adaptive control [14]. However, it has been shown that there is still a requirement for simple, integrated energy management methods that provide remote control and real-time energy consumption monitoring [15]. Such methods have been presented for building systems by Marinakis et al. [6] and Doukas et al. [7].

The advancement of integrated, real-time energy management in building cooling systems is presently not developed to the same degree in industrial processes that are often more energy intensive [16]. Lee et al. [16] developed an energy management system to be used together with facility monitoring and control systems (FMCSs). This system monitors and optimises HVAC and chiller energy consumption of industrial information technology (IT) plants. Vosloo et al. [17] developed a method that simulates, optimises and controls the water reticulation network of a deep level mine. There is a need for a similar system to be developed for large cooling systems such as found on deep level mines.

South African deep level mines have large, uniquely integrated water and air cooling systems to meet the cooling demands that result from increased mine depths and the associated high temperatures. These systems typically consume more than 20% of total mine electricity supplies [18] while the mining sector accounts for 14% of the national electricity demand [19]. Considering also that industrial energy use accounts for approximately one third of the world's energy demand [20], it becomes clear that more emphasis should be placed on improving the energy efficiency of large mine cooling systems.

This paper presents a simple, integrated, real-time energy management system that can be applied to a variety of large cooling systems as found on deep mines. The system is presented as a typical example of a generic, integrated energy management tool and

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used to illustrate the potential benefits that may be realised from such systems. Integrated real-time control and optimisation of subsystems are combined with automatic reporting and remote monitoring. Results from *in situ* experiments on various mine cooling systems with different operational processes are presented. The main objective is to address the need for a practical, real-time energy management system of a cooling system, applied to an energy intensive industrial process such as found on mines.

A detailed case study has been presented in which the effects of the developed energy management system on energy consumption, service delivery and system performance were analysed for one specific deep-mine cooling system [21]. This paper presents the functional details of the developed energy management system and further expands its application by considering results from four significantly different large mine cooling systems. The application of the new system to various mine cooling systems as well as the shown potential for expansion to other large cooling systems emphasise the system's generic approach to the energy management of various large integrated cooling systems. It highlights an integrated systems approach to energy efficiency and its practical significance to sustainability, as recommended by Chai and Yeo [20].

2. Large mine cooling systems

The service delivery requirements and operation of integrated mine cooling systems differ from typical building HVAC systems. Large volumes of mine water are continuously chilled, stored and supplied to an integrated network of end-users. Typical operational processes and relevant energy efficiency and control methods are necessary considerations when developing an integrated energy management system.

2.1. Operation

Deep mines require chilled water for a variety of purposes. These include bulk cooling of ventilation air, cooling of rock drills and other machinery, rock sweeping operations, dust suppression and underground cooling cars or spot coolers [22]. The combined cooling capacity required as a result of these operations is typically 30 MW or more [23]. Large and uniquely designed, integrated cooling systems are required. Such systems are installed on the surface and underground as integral parts of typical semi-closed loop mine water reticulation systems [24].

Fig. 1 shows the schematic process layout of a generic mine cooling system, indicating typical subsystem interaction, water flow, electrical energy input and thermal energy flow into and out of the system. Hot water from the end-users enters a storage dam at about 30–35 °C from where the water is pumped though pre-cooling towers. These are usually forced draught direct contact heat exchangers that cool the water down to just above ambient temperature [25]. The pre-cooled water is then pumped through large water-cooled chillers where the temperature is reduced to approximately 2 °C. The arrangement and size of the chillers depends on the requirements of each specific mine. Chiller cooling water is pumped through another set of cooling towers where heat is transferred to ambient.

Chilled water is either sent directly to the working face and various underground end-users or pumped through bulk air coolers (BACs) [26]. A BAC is an evaporative cooler that cools incoming ambient air to ensure that the legally required wet-bulb temperature of 27.5 °C or less is maintained underground [17].

Demand for chilled water underground is sporadic and usually relatively unpredictable as a result of the complex network of end-users. The location and size of the chilled water storage dams therefore play important roles in ensuring that the varying demands of each specific mine can be met [27]. The network of storage dams is usually interconnected to allow the bypass and/or recirculation of water as required by variations in operating conditions.

Electrical energy input is provided to the chiller compressors and auxiliary equipment such as cooling tower fans, BAC fans, chilled water pumps, cooling water pumps and various transfer water pumps. Thermal energy is transferred from the water in the pre-cooling towers, condenser cooling towers and chiller evaporators. Thermal energy is transferred to the water in the BAC and chiller condensers.

Various different process designs and operational procedures accommodate mine-specific cooling loads and requirements. A system with multiple parallel chillers is typically used when the cooling load is primarily determined by seasonal changes in water volume requirements. A parallel arrangement of chillers that are linked in series is common when there are also seasonal variations in inlet water temperature [28]. Separating two sets of chillers with an intermediate storage dam in a cascade layout is another method to accommodate temperature and flow variations.

Closed loop cooling systems that only supply water to a BAC and therefore feature no storage dams exist in cases where chilled service water is supplied to the mine by an alternative source. In certain special applications ice-making plants have also been incorporated with chilled water systems to provide additional capacity or serve as thermal storage systems [29]. Underground cooling systems generally have similar designs as surface plants but have significantly different operating conditions and are therefore specified and controlled accordingly.

It is apparent that the effective energy management of mine cooling systems depends on at least two operational characteristics. First, the interdependent operation of the subsystems and the various flows of thermal and electrical energy must be collectively and optimally managed as an integrated system. Second, the wide spectrum of design variations must be accommodated by a sufficiently generic management tool in order to be practically feasible.

2.2. Energy efficiency

Improving the energy and cost efficiency of mine cooling systems have been investigated by various studies. Del Castillo [30] investigated the use of air cycle refrigeration systems instead of water-supplied BACs to provide cool ventilation air and thereby save energy costs associated with chilling and pumping water. Swart [31] considered the optimisation of electricity costs of underground chillers and ventilation fans by developing a load shifting model. Pelzer et al. [32] developed a strategy that reduces and controls the inlet water temperature of chillers to improve the coefficient of performance (COP), defined as the ratio of chiller cooling load to chiller compressor power.

These strategies have contributed to the improvement in energy efficiency of mine cooling systems. However, a central energy management system that not only controls specific subsystems according to energy efficient strategies, but also monitors and manages the integrated system and its auxiliary equipment optimally has not been developed.

There is a strong correlation between energy efficiency and control systems [33]. Investigations to optimise control systems of mine ventilation systems have been made over the years [34–36]. Complex mathematical models have also been introduced in the optimal control of large cooling systems in other sectors [37–39]. However, the majority of these systems do not simultaneously address the concerns of operational efficiency, control robustness and computational costs [40]. Their complexity therefore generally

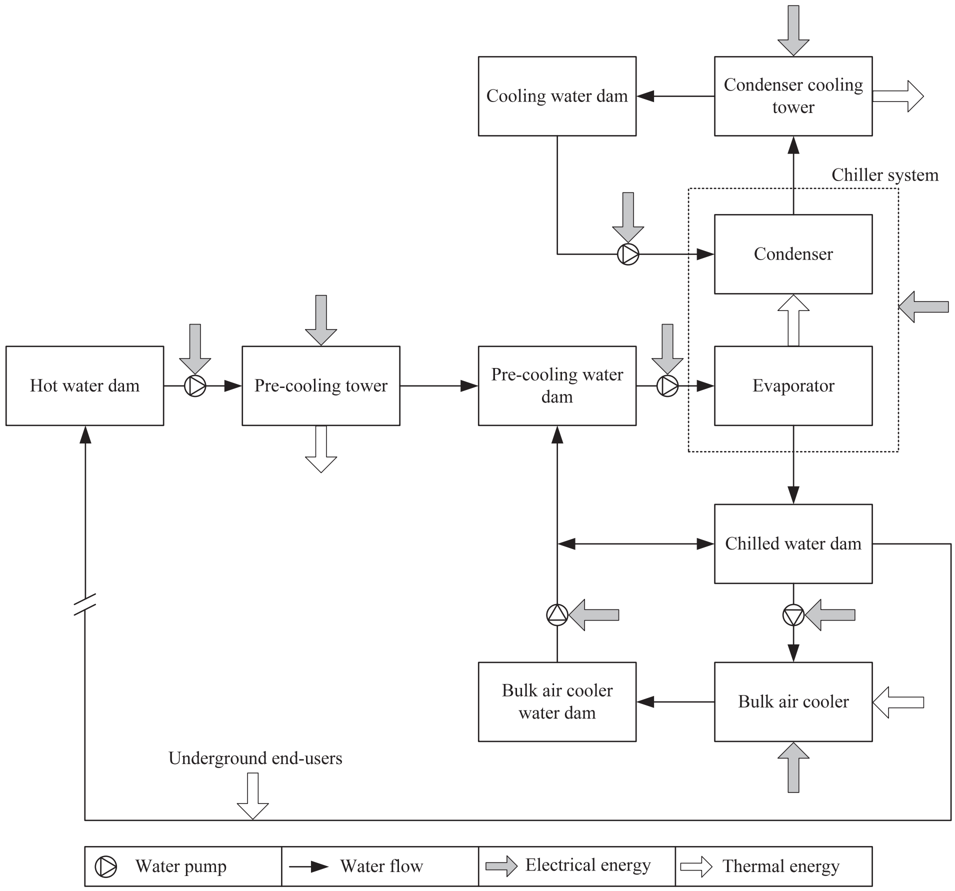

Fig. 1. Schematic of a generic mine cooling system.

leads to unreliable, impractical implementation [41]. It therefore 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.

3. Energy management system description

An energy management system called Real-time Energy Management System for Cooling Auxiliaries (REMS-CA™) was developed as a typical example of a central energy managing tool for large mine cooling systems [42]. The focus of the tool is a generic systems approach to energy efficiency and integrated energy management. Features include a robust supervisory and functional specification, a simple optimisation and hierarchical control system, an automatic reporting system and an easy-to-use interactive monitoring platform.

3.1. System architecture

The energy management system integrates with existing mine communication networks as a hierarchical cascade controller, as shown in Fig. 2. This system architecture involves inner control loops managed by a network of local programmable logic controllers (PLCs) and an outer control loop managed by a central supervisory, control and data acquisition (SCADA) system. This ensures complete control and monitoring of the entire PLC network and is therefore a popular approach to data acquisition [43] and centralised energy management [44].

The REMS-CA™ server communicates with the mine SCADA client via the OPC protocol (Object linking and embedding for Process Control) [45]. This protocol ensures the real-time exchange of data between two independent platforms. It therefore enables the energy management system to write and read values to and from the master PLC and hence interact with all field instrumentation and actuators, as shown in Fig. 2. The OPC connection enables the system to be integrated to any mine SCADA and thereby ensures a generic energy management tool.

The information flux between the SCADA and PLCs is typically enabled through an Ethernet or Profibus network. Such networks are well-proven and therefore permit simple accessibility to all subsystems.

The energy management system server is accessed through an interactive user interface, usually viewed from a personal computer (PC). This allows the user to monitor and control the energy management system in conjunction with the existing SCADA system. Field controllers also have human–machine interfaces (HMIs) to enable preferential control in case of emergencies.

3.2. Functional specification

Fig. 3 shows the key functionalities of REMS-CA™ as an energy manager. After the system is customised for a specific cooling system via a user friendly visual editor suite, preferences can be provided on the user interface. Such preferences typically include allowable control limits of equipment and specific subsystem set points to ensure that service delivery requirements are met. The high-level outputs are real-time monitoring of energy usage and all system parameters, real-time optimisation and control of sub-

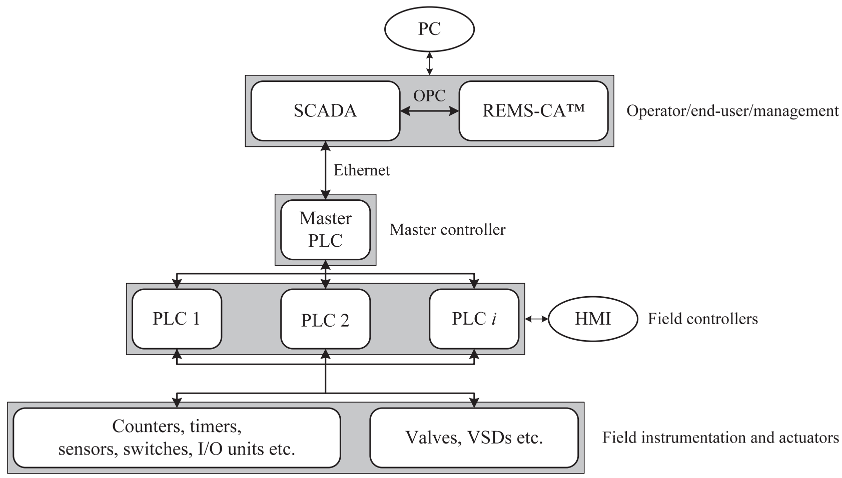

Fig. 2. Integrated control system architecture.

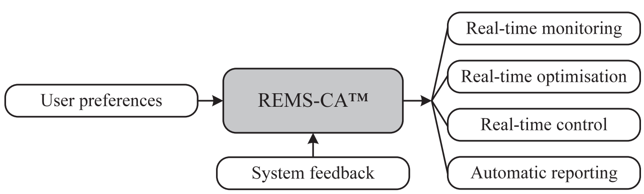

Fig. 3. Key functionalities of the energy management system.

system and auxiliary equipment and the automatic daily, weekly and monthly reporting of energy consumption and its management.

A typical main overview window of REMS-CA™ is shown in Fig. 4. This figure shows the integrated layout of the specific mine cooling system as well as all the automatically controlled actuators, in this case a variety of variable speed drives (VSDs) and control valves. Various screen tabs can be navigated, settings can be customised and manual and automatic modes can be selected. The layout of the interface is colourful, intuitive and easy to use by the operator, as recommended by Avouris [46].

A robust specification for the various communication and control scenarios between REMS-CA™, the SCADA, PLCs and cooling system is important. Redundancy must be built into the computerised management system to ensure that it is practical for implementation as an automatic plant controller.

Fig. 5 shows the communication and control paths specified for the connection of REMS-CA™ to existing cooling system networks. REMS-CA™ has automatic and manual control modes. This allows the user to choose between automatic set point optimisation and manual set point overriding under special circumstances. The SCADA is developed to include the option of providing REMS-CA™ with control permission. PLCs can generally be controlled locally from the HMI or automatically from the central SCADA.

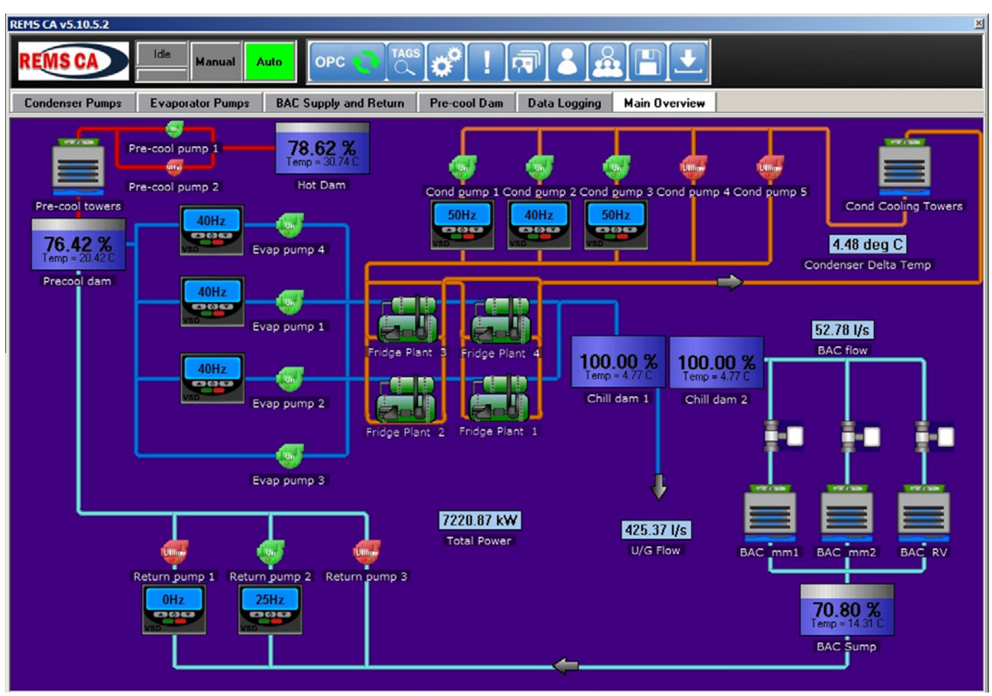

Fig. 4. Example of a main user interface in the energy management system.

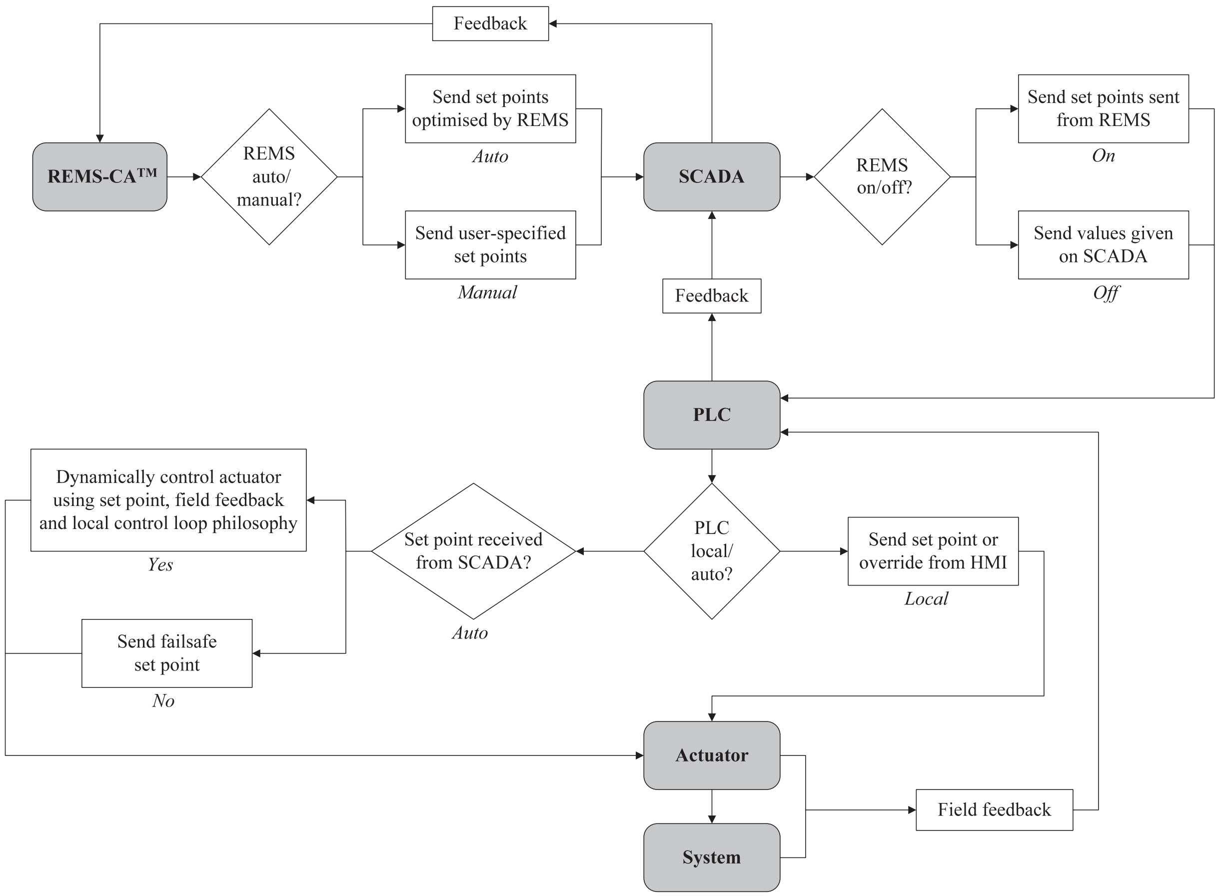

Fig. 5. Control network communication specification.

The flow chart in Fig. 5 indicates that the various options of the control loop are specified so that control will never be relinquished. Optimal performance can be expected when all PLCs are in automatic inner control mode, control permission is given by the SCADA and REMS-CA™ is in automatic outer control mode. In addition to the communication requirements as specified, a backup REMS-CA™ server ensures automatic fail-over transfer to a mirrored platform. Redundancy is therefore built into the system and it can be considered suitably robust for practical application to mine cooling systems.

3.3. Control and integration

The main objective of the control capability of the energy management system is to control the subsystems and auxiliary equipment to optimise the electrical energy consumption of the integrated cooling system. This is done as simply as possible to minimise computational time and costs and to improve the service, upgradeability and maintenance of the system long after implementation.

Typical examples of controlled cooling system equipment include chilled water pumps, cooling water pumps and BAC supply water valves. VSDs are typically used to control the shaft speed of pump motors and therefore also the motor energy consumption and water flow rate. Electric or pneumatic actuators are typically used to control the position of water valves and thereby also the water flow rate.

A generic controller function is available in REMS-CA™. This function can be edited by the user to select a specific subsystem and appropriate local control philosophy. As an example, Fig. 6

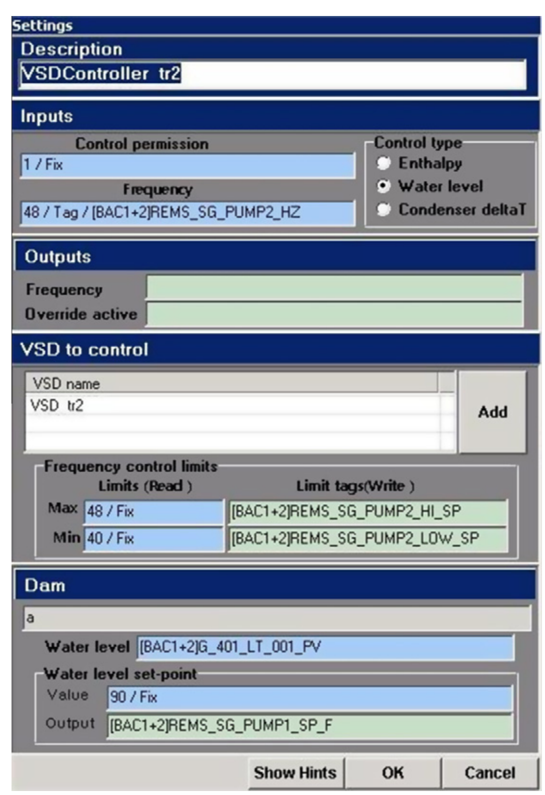

Fig. 6. Example of a generic VSD controller in the energy management system.

shows the edit window of a generic VSD controller. It is possible to select the water level of a dam, water temperature difference or ambient enthalpy as the control parameter of this controller, depending on the specific system and VSD application. Multiple controllers can be inserted and created within the system, as determined by the site design and required control parameters.

Fig. 7 is a schematic summary of the integrated control and optimisation process of typical generic controllers within REMS-CA™ as applied to the generic mine cooling system shown in Fig. 1. It can be seen that various generic controllers can be created and customised to communicate with various plant PLCs. The control and optimisation procedures are customised depending on the type of equipment being controlled and the relevant subsystem interaction.

The method of hierarchical control and optimisation is shown in Fig. 7 by considering Controller 1 as an example. In this case, the controller is set up to control the chilled water pump speed by means of a VSD. The user first defines VSD frequency control limits that are determined during commissioning. The type of set point is then selected. In this case, the pump will be modulated to maintain a chilled water dam level set point. The value of the dam level set point is then optimised by the energy management system by considering various parameters. If a defined override value or mine scheduled value is not present, the system minimises the upper frequency limit through simple embedded control algorithms. In this case, the objective is to ensure that the chiller loading is as low as possible while maintaining 10% deviation of the required chilled water temperature, chilled water dam level and pre-cooling dam level at all times. The subsequent outputs are energy-optimised set points and frequency limits which are sent to the relevant PLC to implement and control locally by means of a proportional–integral–derivative (PID) control loop.

Other subsystem control methods are implemented by the energy management system analogously to the example shown. The cooling water pump is controlled according to a water temperature set point across the chiller condenser. The bulk air cooler pump is controlled by a feed-forward control loop according to the ambient enthalpy. The bulk air cooler return pump is modulated to maintain a set bulk air cooler water dam level. The pre-cooling pump is controlled according to a pre-cooling water dam level.

The developed energy management system therefore allows for simple control and optimisation of each controlled subsystem while taking into account the real-time interaction with other subsystems. An advantage of the outer-loop controller functions in the energy management system is that a large number of subsystems can be optimally controlled in an integrated manner without increased computational cost. Furthermore, the generic design of the controllers allows adaptability to various mine cooling system layouts. Electrical energy of integrated cooling systems on different sites can thus be optimally managed in real-time by using the same basic energy management tool, customised for each individual plant.

3.4. Monitoring and reporting

A real-time supervisory monitoring functionality supports the control tools to achieve integrated energy management. This is made available as a separate tab in the REMS-CA™ platform with various monitoring, statistical and graphical display tools available to the user. Typical examples include the graphical tracking of daily power consumption of the overall cooling system or its subsystems, tracking of critical system parameters such as dam levels or temperatures and the real-time calculation of cost savings realised by the management system. An automatic alarm system can also be set up to alert the user to abnormal energy usage, system performance or network-related issues. Fig. 8 is an example of a customised monitoring page in the system platform.

An automatic reporting and data backup capability supplements the monitoring function of REMS-CA™. This system uses logged plant and power data to automatically create a customised document reporting the energy usage, energy and cost savings, measured against pre-determined baselines, as well as recommended areas for improvement in the operation of the integrated cooling system. These reports are created on a daily, weekly and monthly basis. All reports, alarms and recommendations are available on the system itself or automatically sent via e-mail or mobile phone text messages.

Supervisory energy management systems typically focus on a single primary end-user to monitor the system under consideration [16]. To further develop this concept, the energy management system server is connected to a network that includes all stakeholders involved with the energy efficiency of the cooling system. Such a network is shown in Fig. 9.

The local mine network is typically connected to display monitors both at the plant and at the central control room of the mine. A wireless router further enables the remote connection to external locations such as the control rooms of the Energy Services Company (ESCo) responsible for implementation, mine group energy management or electricity supply utility. The system enables the real-time monitoring function and usage reports to be available to an integrated network of interested parties. This ensures complete energy management by means of a top-down approach since energy-conscious performance is typically of increased concern at managerial level.

4. Experimental validation

Various efforts have been made in the development of virtual methods to evaluate the viability of energy management tools for building systems [47,48]. Similarly, simulation models were initially used to evaluate the feasibility of this new energy management system on various mine cooling systems [49]. Promising virtual results and economic feasibility led to the implementation of REMS-CA™ on four large mine cooling systems.

Details of the design, features and specifications of the four cooling systems considered are given in Table 1. There are distinct differences in the configurations and operational methods of the four sites. Collectively they encompass the most typical cooling system arrangements found on deep level mines. Important *in situ* experimental results from each of the sites are presented to investigate the feasibility, practicality and versatility of REMS-CA™ as a typical example of a central, integrated energy management system.

Accurate measurement of data and energy savings from industrial energy efficiency projects can alleviate any uncertainty about the efficacy of such projects and improve future estimates of expected savings on similar systems [50]. Therefore, principles given in *The Measurement and Verification Guideline for Energy Efficiency and Demand-Side Management* (*EEDSM*) *Projects and Programmes* published by Eskom's Corporate Services Division Assurance and Forensic Department are followed to verify energy saving results [51]. These principles conform to the measurement and verification specifications for energy saving projects given by the South African Bureau of Standards [52].

Using regression models to accurately determine daily energy savings in cooling systems is a widely used industrial verification method [50,51]. Suitable scaling parameters were therefore identified for each site by an independent auditor and used to calculate, on a daily basis, what the cooling system power would have been before implementation of the energy management system.

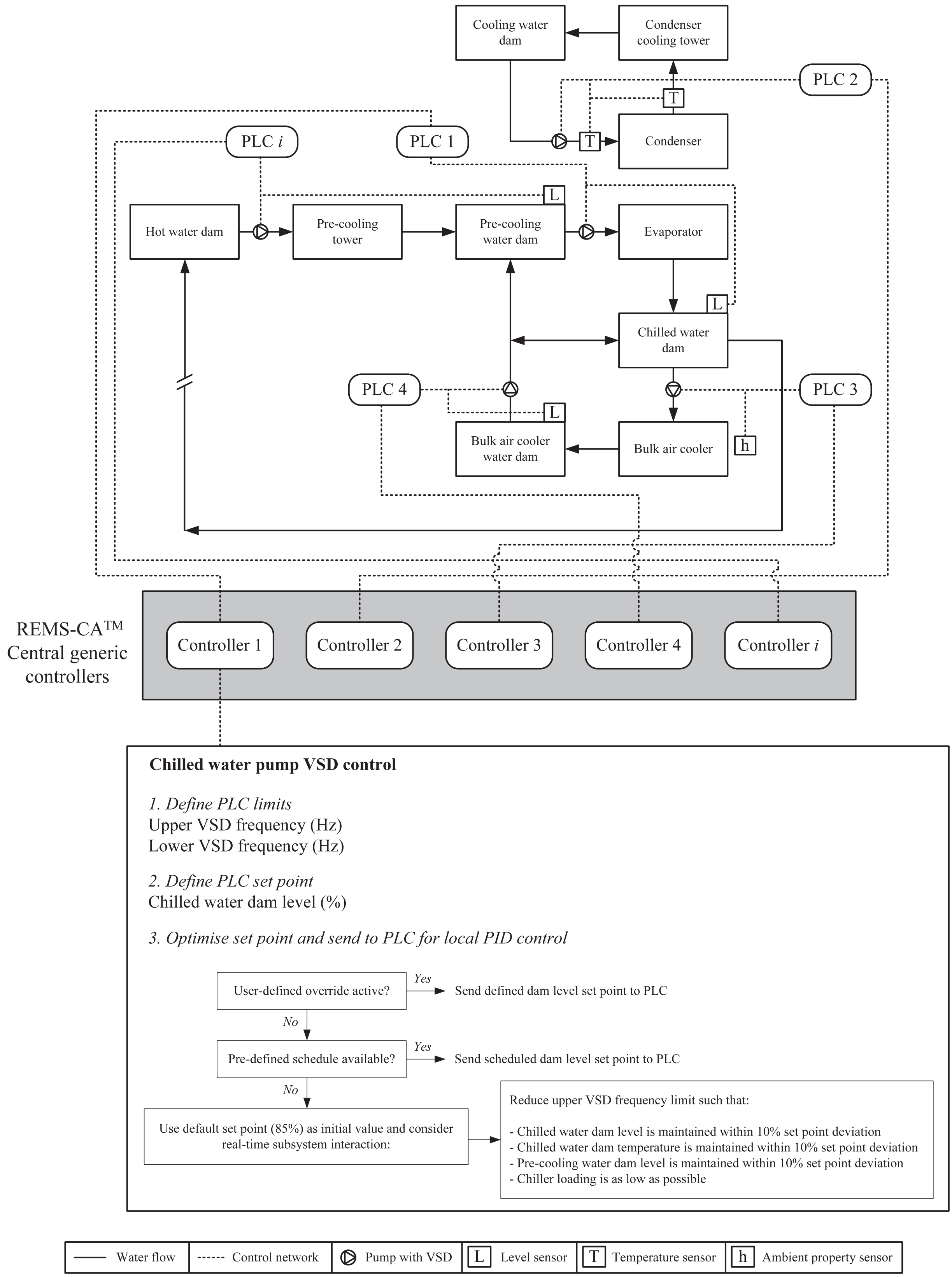

Fig. 7. Optimisation, control and integration process of generic controllers.

Fig. 8. Example of an energy monitoring page in the energy management system.

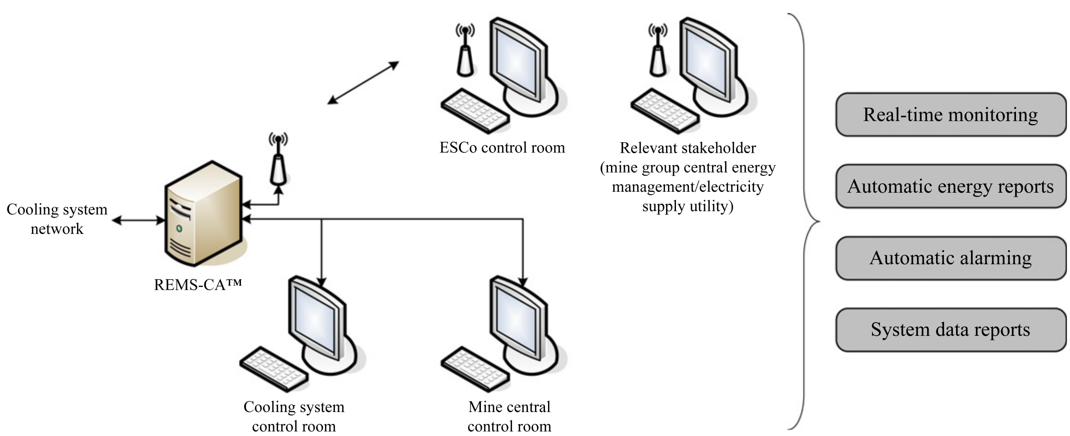

Fig. 9. Integrated network for monitoring and reporting.

4.1. Parallel chiller system

The first cooling system on which REMS-CA™ was installed uses six parallel chillers to provide the variable water flow demand during different seasons at this mine.

The energy efficient equipment installed on this system include VSDs on all the pre-cooling, chilled, cooling and BAC water pumps. The energy management system controls the speed of all the VSDs by optimising the various parameter set points in an integrated manner. Local control parameters include the chilled water dam level, cooling water temperature rise, ambient enthalpy and pre-cooling water dam level. Multiple chiller loading is also considered in real-time to determine the optimal number of parallel chillers required to meet the underground chilled water requirements and that of the BAC.

The daily average power consumption of the combined cooling system before and after implementation of REMS-CA™ is shown in Fig. 10. An evaluation period of three summer months was considered. It is shown that, with the exception of 8 days, positive net savings were reported on a daily basis for the integrated system. An average saving of 1865 kW, or 31.7% of the average pre-implementation baseline, was realised for the considered time period. This translates to an annual operational cost saving of US$784,036.

Variation in daily savings can be expected as shown because factors such as ambient conditions, mine water demands and inlet temperatures all influence the daily cooling demand. The extent to which auxiliary equipment and chiller loading can be optimised therefore depends on daily requirements.

It was found that an average chilled water volume of 17.5 Ml/day was sent underground during similar conditions before implementation. This was reduced by 6.9% after implementation. However, the lowest daily flow before implementation was 5.8 Ml/day while after implementation it was 7.6 Ml/day. This

Table 1
Details of cooling systems used for validation.

	Parallel chiller system	Parallel-series chiller system	Cascade dam system		Bulk air cooler system
System layout					
Service delivery parameters supplied	Chilled water, cool ventilation air	Chilled water, cool ventilation air	Chilled water		Cool ventilation air
Number of hot water dams	1	1	3		–
Number of pre-cooling towers	2	8	2		–
Number of chillers	6	4	5		4
Layout of chillers	Parallel	2 Parallel groups, each with 2 chillers in series	4 Parallel feeding an intermediate cool dam, last chiller after cool dam		Parallel
Number of condenser cooling towers	6	4	3		4
Layout of condenser cooling towers	Parallel	Parallel	Parallel, separate to 2 cascade systems		Parallel
Number of chilled water dams	1	2	3		–
Number of BACs	3	3	–		1 (2-stage)
Number and layout of chilled water pumps	6 Individual	4 Parallel	5 Individual		5 Parallel
Number and layout of cooling water pumps	6 Individual	5 Parallel	5 Individual		5 Parallel
Number and layout of BAC water pumps	3 Individual	3 Parallel	–		5 Parallel
Number and layout of pre-cooling water pumps	4 Individual	3 Parallel	2 Parallel		–
System specifications					
Hot water dam temperature (°C)	26	30	26		–
Chilled water dam temperature (°C)	3	6	2.5		11
Volume of water sent underground (Ml/day)	20	27	19		–
Combined cooling capacity (kW)	39,000	42,000	26,000		24,000
System COP	5.5	5	6		5.5
Chiller specifications			*4-group*	*Single*	
Cooling capacity (kW)	6500	13,300	5000	6000	6000
Evaporator outlet temperature (°C)	3	5.9	6.5	3	2
Condenser inlet temperature (°C)	27	18.5	22	22	21.4
Evaporator water flow rate (l/s)	250	300	115	300	140
Condenser water flow rate (l/s)	450	600	300	380	210
COP	5.5	6.65	6	5	5.5
Refrigerant	R134a	R134a	R134a	NH_4	NH_4
Compressor type	Centrifugal	Centrifugal	Centrifugal	Screw	Screw
Water pump specifications					
Chilled water pump rating (kW)	110	90	55	183	132
Cooling water pump rating (kW)	160	185	132	183	110
BAC water pump rating (kW)	75	75	–	–	75
Pre-cooling water pump rating (kW)	70	–	70		–
Cooling tower specifications					
Pre-cooling tower water outlet temperature (°C)	24	24	14		–
Condenser cooling tower water outlet temperature (°C)	27.5	27.5	27.5		22.5
Ambient air inlet wet-bulb temperature (°C)	22	22	22		18
BAC water outlet temperature (°C)	9	14	–		11
BAC air outlet wet-bulb temperature (°C)	7	9	–		8

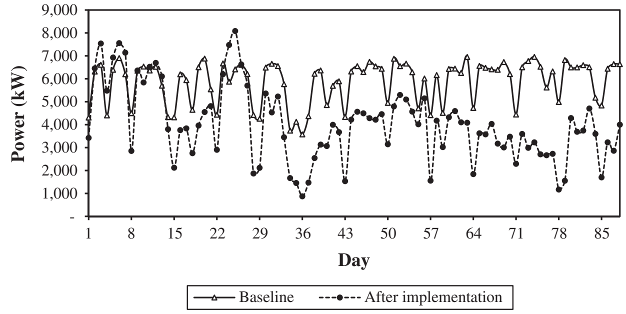

Fig. 10. Daily average power consumption (parallel chiller system).

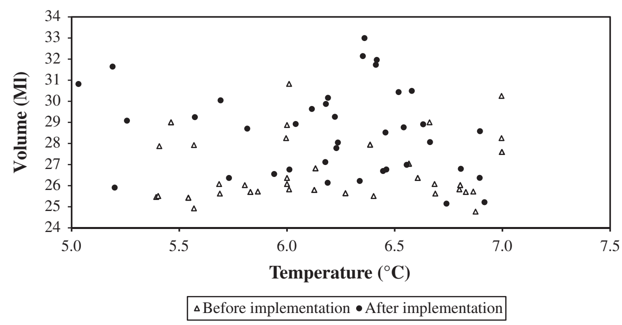

Fig. 11. Daily average chilled water dam temperature and water volume sent underground (parallel-series chiller system).

means that, even though the average flow was reduced somewhat, the availability of chilled water to underground end-users did not decrease.

The daily average chilled water temperature increased from 3.8 °C to 4.3 °C after implementation. This is mainly a result of the variations in chilled and cooling water flow rates influencing the performance of individual chiller capacity control. However, this mine requires the water temperature to remain below 5 °C. The small increase in chilled water temperature is still less than the maximum temperature specified by the mine.

Personnel monitored the energy performance of the cooling system from the central mine control room as well as remotely from the central energy management offices. This functionality, as well as the automatic daily reports, was used to actively engage in the energy management process. On-site operators were contacted on various occasions to investigate the performance or maintenance-related issues of subsystems for which energy inefficient operation were reported by REMS-CA™. Not only were large direct savings realised by the systems approach of the energy management tool, but indirect savings resulting from the active energy management support tools were also achieved.

4.2. Parallel-series chiller system

REMS-CA™ was also implemented at a mine with two chillers in series, connected in parallel with another identical set of two series chillers. It is thus known as a parallel-series chiller system and provides the mine flexibility in terms of chilled water temperature as well as flow demands. Results of one month of implementation on this system were used to evaluate detailed effects on subsystem performance in Ref. [21]. Results of two more implementation months are used here to consider the more generalised effects of the new energy management system and to effectively compare it to the other systems presented in the paper.

Energy efficient equipment installed at this mine include VSDs on three chilled water pumps, three cooling water pumps and two BAC pumps as well as three control valves on the BAC water supply lines. REMS-CA™ collectively controls all these subsystems, similar to the first cooling system. However, these pumps supply subsystem manifolds. The control and optimisation procedures are therefore adapted to control a pump group rather than an individual pump. Also, optimal chiller loading cannot be considered in the same way as with parallel chillers only. Factors such as the water temperature interaction between lead and lag chillers in series are therefore also considered in the optimisation procedure for this cooling system.

The reduction in total system power consumption was reported to be 32%, 41% and 36% for three summer months, respectively. On average the system power was reduced from 7 361 kW to 4 752 kW for the evaluation period. The saving translates to 35.4% of the baseline power consumption, equivalent to a cost saving of US$1,095,611. Variation in daily savings was less than for the first cooling system, primarily as a result of the fewer options available regarding multiple chiller loading.

Fig. 11 shows the daily average chilled water dam temperature and total volume of water sent underground before and after implementation. It is shown that before implementation the chilled water dam temperature varied between 5.3 °C and 7 °C with a design point of 6 °C. Also, the typical volume of chilled water sent underground varied between 24.5 Ml/day and 30.5 Ml/day with a design point of 27 Ml/day. The upper limit of the temperature and lower limit of the volume can thus be considered as the parameters within which the service delivery of the mine must be maintained.

It can be seen that the average chilled water dam temperature after implementation remained below the upper limit, averaging at 6.4 °C. This is only a marginal increase in service water temperature resulting from the decreased chilled water flow and decreased BAC water usage. It is apparent that the chiller capacity control functioned as designed by maintaining the set point outlet temperature for varying water flow rates, given that the flow rates are within limits allowed by the machine. The small increase in average temperature can be attributed to the new control method of maintaining a set dam level. This requires a large volume of water to remain in the dam for longer periods, resulting in a slightly larger temperature increase. However, chilled water below 7 °C is acceptable for this mine.

Fig. 11 also shows that the volume of water sent underground was 27.4 Ml/day, which is still above the lower limit of 24.5 Ml/day. This indicates that there was no reduction in service water supply and availability as a result of the reduced chilled and BAC water flow rates.

The effect of the energy management system on the efficiency of an integrated cooling system can be evaluated by considering the system COP. This is defined as the ratio of total cooling load to total electrical energy input of the cooling system. Fig. 12 shows the daily average system COP before and after implementation as well as the associated thermal load of the combined cooling system.

Fig. 12 shows that although the combined cooling loads remained within the same range, the system COP increased by 36%. This result indicates that the cooling load of the entire plant, or the overall service delivery, was not compromised while the total electrical energy consumption was reduced significantly. The COP is shown to be similar before and after implementation for very high thermal loads. This is to be expected because days of high thermal demand will require higher electrical energy input with less scope for optimisation. This means that, as the loading on the system decreases, the potential for a central energy management system to realise part-load savings by matching the water supply to the demand increases.

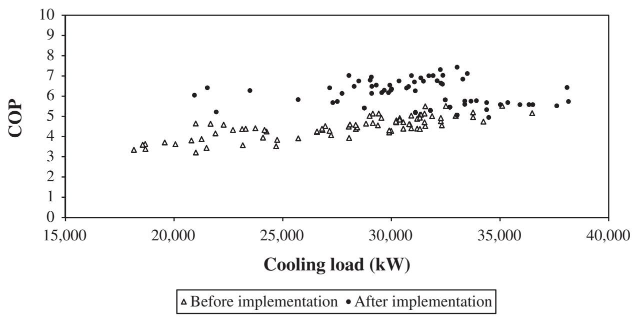

Fig. 12. Daily average system COP (parallel-series chiller system).

4.3. Cascade dam system

The third cooling system used to validate REMS-CA™ uses four parallel chillers supplying water to an intermediate storage dam. Outlet water from this dam is pumped through a single chiller before it enters the final chilled water storage dams. The layout therefore features cascade dams separated by a chiller. This scheme allows for flexible thermal storage and also accommodates flow and temperature requirement variations. However, the mine typically operates one chiller from both groups full-time and allows any excess water to be recirculated.

REMS-CA™ controls VSDs installed on all chilled water and cooling water pumps. Optimal scheduling of the two cascade sets of chillers is also considered. This is an important feature on this site because the storage dams provide the potential for thermal storage during peak times given that typical end-user water demands and the interdependency of the cascade chiller systems are taken into account.

Fig. 13 shows the typical daily power consumption profile of the integrated cooling system. The variations in the post-implementation profile are attributed to the optimal scheduling and loading of the two chiller systems. From 23:00 to 02:00, one chiller in each system is operated just to maintain the two sets of dam levels according to the underground water requirement for rock sweeping operations during this time. This is followed by a period where more chillers are run in order to fill up the dams while satisfying the demand underground. From 07:00 to 10:00 all chillers are stopped to maximise cost savings since this is defined as a peak time with high electricity costs. Drilling operations use the stored water during this time. Similar trends in the power profile can be seen during other periods of the day.

It can also be seen in Fig. 13 that the power consumption is reduced significantly during part-load conditions. For example, at 16:00 and 17:00 there is not a large water demand and chillers are only operated to maintain the existing dam levels. Water flows are therefore reduced significantly, leading to a part-load saving of about 400 kW.

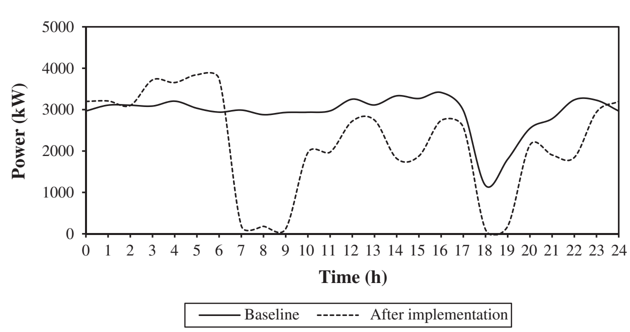

Fig. 13. Typical daily power profile (cascade dam system).

The savings realised for the day shown in Fig. 13 amount to 702 kW, or 24% of the baseline. For an assessment period of two months, the average saving achieved was 606 kW, or 29.3% of the baseline power. The associated annual cost saving is US$254,925.

The service delivery requirements of this cooling system were improved after implementation of REMS-CA™. The daily water volume sent underground increased by 5.7% to 12.58 Ml/day while the average chilled water temperature decreased by 10.3% to 6.6 °C. It is therefore apparent that the energy management of cascade chillers based on a systems approach not only improves its energy efficiency, but also its output requirements.

4.4. Bulk air cooler system

The final mine cooling system where REMS-CA™ was implemented operates in a closed loop water circuit, involving four parallel chillers that supply chilled water to a surface BAC. There are therefore no large water storage dams.

Energy efficient equipment controlled by REMS-CA™ include three VSDs on the chilled water pumps, three VSDs on the transfer pumps to the first stage of the BAC, three VSDs on the cooling water pumps and isolation valves of the cooling water line through each chiller. Optimisation considerations for this site include variation of the chilled and transfer water flow rates as functions of ambient enthalpy and BAC drainage dam levels, variation of cooling water flow rate to maintain a constant water temperature rise and optimal chiller, pump and BAC fan loading. Valves are also used to automatically isolate offline chillers to prevent unnecessary pumping of water.

After two months of evaluation during the summer, it was reported that the daily average power usage of the combined system was reduced to 2245 kW from 3394 kW. This is a 33.8% average saving, translating into an annual cost saving of US$482,658.

It is important to consider the wet-bulb temperature of the BAC outlet air that enters the ventilation shaft in conjunction with the energy savings. Fig. 14 shows the daily average power consumption as a function of the average shaft wet-bulb temperature achieved for comparable conditions before and after implementation.

Fig. 14 shows that the average wet-bulb temperature of the air entering the shaft increased from 7.4 °C to 7.9 °C, or by 7.1%. This is not a large increase considering the significant electrical power savings that were realised. Considering that the only temperature restriction at this mine is that the shaft inlet air temperature must not exceed 10 °C, it is apparent that the ventilation air was significantly overcooled before implementation. It is therefore also possible to realise large electrical energy savings on a closed loop BAC system, while maintaining service delivery requirements, by considering the optimal management of subsystem energy usage.

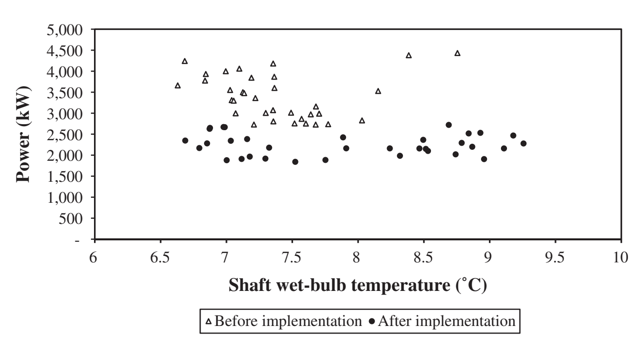

Fig. 14. Daily average power and ventilation air wet-bulb temperatures (bulk air cooler system).

Table 2
Costs, cost savings and payback periods of energy management system implementation.

	Additional equipment cost (US$)	System integration cost (US$)	Total cost (US$)	Annual cost saving (US$)	Payback period (months)
Parallel chiller system	330,949	296,280	627,229	784,036	10
Parallel-series chiller system	508,122	85,720	593,842	1,095,611	7
Cascade dam system	139,567	222,295	361,862	254,925	17
Bulk air cooler system	118,720	99,704	218,424	482,658	5
Average	274,340	175,999	450,339	654,308	10

4.5. Economic feasibility

An energy management solution will only be viable for implementation and further consideration if it demonstrates economic feasibility. This is typically evaluated by considering the initial and running costs, the cost savings and the simple payback period, defined as the ratio of costs incurred to costs saved per time period [53]. These factors were evaluated for the four sites used for *in situ* validation and are shown in Table 2.

The implementation costs of an energy management tool depend on the extent of additional equipment or alterations required and the system integration work that is necessary. The costs shown in Table 2 are the actual total costs that were incurred to implement the developed energy management on the various sites. Equipment costs include new VSD installations, control valves, measurement instrumentation and additional equipment such as power and instrumentation cables. System integration costs include software costs, PLC and SCADA alterations to enable the new energy management system to function as specified. Only initial investment costs were considered since there are no significant recurring costs involved after installation.

It can be seen that the total costs varied between US$218,424 and US$627,229. These costs are site-dependent. It was found that the costs for some sites, such as the parallel-series system, were dominated by equipment. Other sites, such as the cascade dam system, required more system integration work.

Table 2 shows that cascade dam system has the longest payback period of 17 months. This is mainly because of high system integration costs caused by a lack of existing communication network infrastructure. The bulk air cooler system has the shortest payback period of 5 months. This is attributed to modern control infrastructure on this site leading to low integration costs. The average payback period is 10 months.

The payback periods for all the sites were found to be less than 2 years. This generally indicates good viability for an energy management system, particularly when similar technological features are involved [54]. It can therefore be concluded that the payback period analysis of the four sites on which the new energy management system were implemented indicates that the system is economically feasible.

4.6. Summary

REMS-CA™ was implemented on four large mine cooling systems with cooling capacities ranging from 24 MW to 42 MW. The operations and processes also differed significantly. It was found that, on average, electrical energy savings of 33.3% were realised. This is a combined power reduction of 6 229 kW and translates to a combined annual cost saving of US$3,271,538.

It was found that the payback periods for the four mines under consideration ranged from 5 to 17 months, with an average of 10 months. The generic energy management tool can therefore be considered economically viable, especially in cases where insignificant new equipment installations are required and modern communication networks are installed.

Chilled water volumes and temperatures and shaft ventilation air temperatures did not deviate unacceptably on any of the cooling systems. Significant energy savings were thus realised by considering the specific operation, interaction and service delivery requirements of subsystems within each cooling system by a sufficiently simple, integrated systems approach.

The platform servers never malfunctioned during the *in situ* evaluation. In situations where network-related problems surfaced, the specified communication paths ensured that control of the cooling systems was maintained. Real-time optimisation and control was successfully realised on all the sites. The energy management platform was therefore shown to be simple, practical, robust and reliable.

The same software version was implemented on all the cooling systems, with only the user platform and specific controllers customised. This means that the system is sufficiently generic, simple and adaptable to various different operations.

Real-time monitoring capabilities were shown to support the successful day-to-day management of electrical energy usage. Operators and energy managers could take immediate remedial energy-conscious actions when prompted by the system, thus indirectly contributing to energy savings. Similarly, the daily energy usage reports were frequently used by mine management to evaluate and support the energy efficiency of the cooling systems.

5. Expansion potential

It has been shown that the developed energy management system can be feasibly applied to large integrated cooling systems as found specifically on mines. However, the energy management system has the potential to be adapted and applied to other large and suitable cooling systems as well. Two typical examples of such cooling systems are industrial air-cooled heat exchanger systems and industrial wet cooling tower systems.

An industrial air-cooled or dry heat exchanger system involves a closed loop water circuit. The water is pumped through a heat load where it is heated before being pumped through banks of finned tubes that are air-cooled by axial fans. Such systems are typically found where large volumes of demineralised water need to be cooled without coming into contact with the environment. Common examples can be found on power plant subsystems, iron and steel furnace systems and applications that are sensitive to water quality [55].

The potential application of REMS-CA™ on an air-cooled heat exchanger system of a specific steel-making furnace was investigated. The cooling system consists of six water pumps and a heat exchanger with 96 fans. The cooling capacity is 180 MW and the installed electrical input power is 6 600 kW. It was found that the application of the energy management system can potentially save about 1 100 kW by only making small customisations to the existing system.

VSDs will need to be installed on the fans and pumps, indicating that similar equipment will be required as for the mine systems. The monitoring and reporting functionality will remain the same since the steel plant uses the same network principles as found on mines. The hierarchical control principles will also remain unchanged since the PLC network is integrated similarly to that in the mine.

The most significant customisation will involve control set points and system integration. A cold-water temperature set point will be added to the generic VSD controller shown in Fig. 6. The main limiting optimisation parameter will be the supply-water pressure to the furnace to ensure that sufficient water flow will always be supplied. The present set-point optimisation process will be adapted and expanded to take into account furnace operation times, ambient dry-bulb temperature, wind speed and wind direction.

Industrial open-circuit wet cooling tower systems are commonly found where it is less critical to maintain high water quality and make-up water is readily available. Examples are found in electricity generation, petroleum-, chemical- and most manufacturing environments [56]. The expansion of the developed energy management system to these systems will be similar to the adaptation described for air-cooled heat exchangers. Additional optimisation parameters will include the cooling tower supply-water pressure and process-dependent requirements. Further customisations will depend on site-specific control network structures. These are not expected to be significant because most industrial plants operate with SCADA and PLC networks similar to those found on mines [57].

Although this paper focuses on mine cooling system applications, it is apparent that there is definite potential to expand the use of the developed energy management system. Relatively few alterations would be required to adapt REMS-CA™ specifically to large integrated air-cooled cooling systems and closed loop wet cooling tower systems. These expansions merit further investigation. This will be reported in future papers as the energy managing tool is developed further and implemented in more industries.

6. Conclusions

Cooling and ventilation is an electricity demand sector in which various load management efforts have been made. It was found that there is still the need for a simple, integrated, practical, real-time energy management tool. This specifically pertains to large industrial cooling systems such as mine cooling systems for which, at present, no such tool is available.

An energy management system called REMS-CA™ was developed to investigate the potential for simple, robust and generic energy management tools that are easy to use on various different large cooling systems. The system connects to mine SCADA systems and features a hierarchical control system that optimises set points of various subsystems by an integrated, systems approach. A real-time monitoring, alarming and reporting function connects to various interested stakeholders and supports the integrated energy management objective.

In situ results from four large cooling system applications with different layouts, sizes and operation were considered as experimental validation. It was shown that an average electrical energy saving of 33.3% was realised for all the sites. Mine service delivery requirements were also never adversely affected. The adaptability, simplicity and robustness of the system were demonstrated. The average payback period was shown to be 10 months. It was shown that there is potential to also apply the energy management system to large air-cooled heat exchanger and wet cooling tower systems. It is apparent that there is significant potential for the future development and application of similar practical systems that manage the energy usage of large cooling systems by means of an integrated systems approach.

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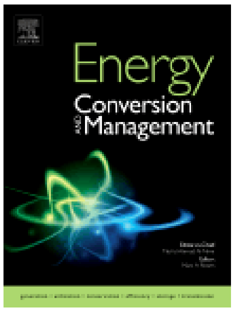

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Annexure D.1

Case study: The effects of a variable water flow energy saving strategy on a deep-mine cooling system

- G.E. du Plessis, L. Liebenberg, E.H. Mathews

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This article focuses on the case study results of the developed strategy on the Kusasalethu cooling system. The energy savings as well as the impact on service delivery and system performance are considered. At the time of article compilation, results from only one month of implementation were available and therefore the results differ slightly from those presented in the thesis report and other articles. The results complement the primary case study of the thesis discussed in Chapters 7 and 8.

See Annexure A.2 for the writer requirements of *Applied Energy*.

This article was also selected, featured and listed in *Renewable Energy Global Innovations* (2013) as part of a compilation of innovative and ground-breaking research contributions made in the international energy sector.

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Case study: The effects of a variable flow energy saving strategy on a deep-mine cooling system

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HIGHLIGHTS

- ▶ Implementation of a developed energy saving strategy for deep-mine cooling systems.
- ▶ Strategy based on variable water flow of integrated cooling system.
- ▶ Real-time control and energy management of integrated cooling system.
- ▶ Case study shows a reduction of 31.5% in total plant electrical energy consumption.
- ▶ Case study shows no adverse effects on service delivery or system performance.

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ABSTRACT

Cooling systems consume up to 25% of the total electricity used on deep level mines. These systems are integrated with the water reticulation system to provide chilled service water to the mine as well as cooling for mine ventilation air. Although there is definite potential for demand-side management on these systems, it is critical that the service delivery be maintained so as not to adversely affect productivity. An energy saving strategy based on variable water flow was developed for the unique demands of integrated mine cooling systems. The strategy is based on matching the evaporators with the demand of chilled water; condensers adapting to the heat load; and the bulk air cooler matching the demand of ventilation air requirements. In this paper, a case study is presented in which the savings and consequences of implementing the developed energy saving strategy are investigated. It is shown that a decrease of 31.5% in overall electrical energy usage is possible without affecting the service delivery or performance of the cooling system.

1. Background

There are increasing global concerns regarding energy management and sustainability. The industrial sector, including the mining industry, uses about 37% of the world's total delivered energy [1]. In South Africa the mining industries use approximately 15% of the national electricity supply [2]. It is therefore reasonable to conclude that the South African mining sector has considerable potential for demand-side management. This will also reduce the electricity supply strain on Eskom, the country's main electricity supply utility [3].

Cooling systems consume up to 25% of the total electricity used on mines [4]. These systems are integrated with mine water reticulation systems to supply chilled service water and maintain safe working conditions underground. Deep level mines have virgin rock temperatures of up to 60 °C [5] and require wet-bulb temperatures below 27.5 °C at underground working areas [6]. Rigorous cooling demands are required and are presenting greater challenges as a result of deeper mining activities and increased surface temperatures. Decreasing the energy usage of deep-mine cooling systems is thus an important demand-side management incentive. It is equally important that service delivery of mining operations be maintained in the process.

A new energy-efficiency strategy to decrease the energy usage of mine cooling systems has been developed. The viability has been demonstrated by means of an integrated mine cooling plant simulation model [7]. The strategy involves the use of existing modern technologies such as variable speed drives (VSDs) and control valves as well as new control methods for water flow based on system constraints unique to deep mines. The integration of these methods is achieved by means of a specialised energy management solution called Real-Time Energy Management System for Cooling Auxiliaries™ (REMS-CA™) [8]. These newly-developed techniques

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Nomenclature

$\dot{m}_{chilled\ dam}$ daily average water mass flow rate from chilled water dam (kg/s)
T_{amb} daily average ambient dry-bulb temperature (°C)
$T_{chilled\ dam}$ daily average chilled water dam temperature (°C)
$T_{hot\ dam}$ daily average hot water dam temperature (°C)
$\dot{W}_{post\text{-}implementation}$ daily average electrical power measured after energy saving intervention (kW)
$\dot{W}_{savings}$ daily average electrical power saving (kW)
$\dot{W}_{scaled\ baseline}$ daily average electrical power calculated by regression model (kW)

have subsequently been implemented on the surface cooling system of the Kusasalethu gold mine in South Africa.

Not only should saving results be quantified and cost effectiveness be evaluated, but the effects of such an initiative on actual mine service delivery must also be examined and monitored to ensure that energy savings do not compromise production. This paper reports on the implementation, results and the effects of this particular energy-efficiency strategy on a mine cooling system. The case study results are also compared to simulated results for other sites. The emphasis is on the energy and cost-saving benefits of the strategy as measured against the effects it has on the mine cooling system, rather than on the details of the developed strategy which will be reported in future papers.

2. Mine cooling system considerations

A deep-mine cooling system is an integral part of the mine water reticulation system consisting of hot water storage dams, pre-cooling towers, refrigeration machines and associated condenser cooling towers, bulk air coolers, and cold water storage dams [9]. Considerations that are important in order to effectively evaluate the implementation of an energy saving intervention will be discussed.

2.1. Service delivery

The foremost priority of a mine cooling system is to enable the complete mine cooling and ventilation system to function properly and reliably [10]. This implies that the chilled water supplied to the mine must always be at the correct temperature and immediately available on demand. The chilled water dam serves as a buffer to accommodate the major flow rate fluctuations in service water [9]. It is therefore important that the level and temperature of this reservoir remain within the required limits after implementing an energy saving intervention. This applies to both the average design values set by the specific mine and the daily profiles which reflect the typical daily mine demands.

A further implication of mine service delivery requirements is that the ventilation air sent underground must always ensure and maintain an acceptable and productive working environment. It has been shown that worker productivity decreases when wet-bulb temperatures exceed 28 °C [10]. South African mines therefore restrict the working area wet-bulb temperature to 27.5 °C [6]. This value must be adhered to in a cooling energy saving intervention applied to the surface bulk air cooler (BAC) system.

2.2. System performance

The performance of cooling system components is also of prime concern when implementing an energy saving strategy. It would be futile to realise short-term energy savings with system components operating inefficiently, resulting in long-term cost increases relating to higher maintenance and replacement costs. Factors which typically need to be evaluated include the coefficient of performance (COP) of both the refrigeration machines and the integrated system as well as the general performance of the water pumps, cooling towers and refrigeration machines.

The cooling efficiency and energy performance of a cooling system is usually defined by the COP which is the ratio of cooling output to electrical input [11]. Both these terms must have the same units. The COP will therefore be dimensionless. When water flow rates are varied, they must be optimally controlled to changing load conditions while counterbalancing adjustments in compressor power controlling components, such as guide vane controllers [12].

The tendency of the COP to increase at decreased evaporator water flow rates and to decrease at decreased condenser water flow rates has been reported [11,13,14]. These trends will be evaluated in the context of this energy saving intervention. With reference to the combined mine cooling system, the COP can be defined as the ratio of total useful refrigeration to total energy input. Since the aim of this intervention is to reduce energy usage while maintaining chilled water service delivery, an increase in this COP will represent a successful application.

The performance of all auxiliary plant equipment must also be considered when implementing the new strategy. All cooling tower supply pressures must remain sufficient to function efficiently. Pumps must be operated within acceptable performance efficiencies when fitted with VSDs. Individual refrigeration machine components must also perform within acceptable limits after the intervention. These are all factors which are not easily predicted during strategy development and must be evaluated after actual implementation.

3. Implementation

The layout of the Kusasalethu surface cooling system, including the newly-implemented infrastructure discussed in this paper is shown in Fig. 1. Used underground water enters the hot water storage dam from where it is pumped through pre-cooling towers into a pre-cooling dam. This water is then pumped through two parallel sets of refrigeration machines before entering the chilled water storage dam. Some of the chilled water is used to cool ventilation air in a surface BAC and then returned to the pre-cooling dam. The remainder of the chilled water is sent underground on demand. Depending on the demand, chilled water can also be returned directly to the pre-cooling dam. Furthermore, coolant water is pumped through each refrigeration machine condenser in a parallel configuration and subsequently cooled by its own cooling towers.

The design specifications of the cooling system and its components are given in Table 1.

The energy saving strategies that were implemented at Kusasalethu include evaporator water flow control, condenser water flow control, BAC water flow control and pre-cooling tower replacement, as shown in Fig. 1.

Three of the evaporator water pumps were fitted with VSDs and are controlled to maintain a specific chilled water dam level while

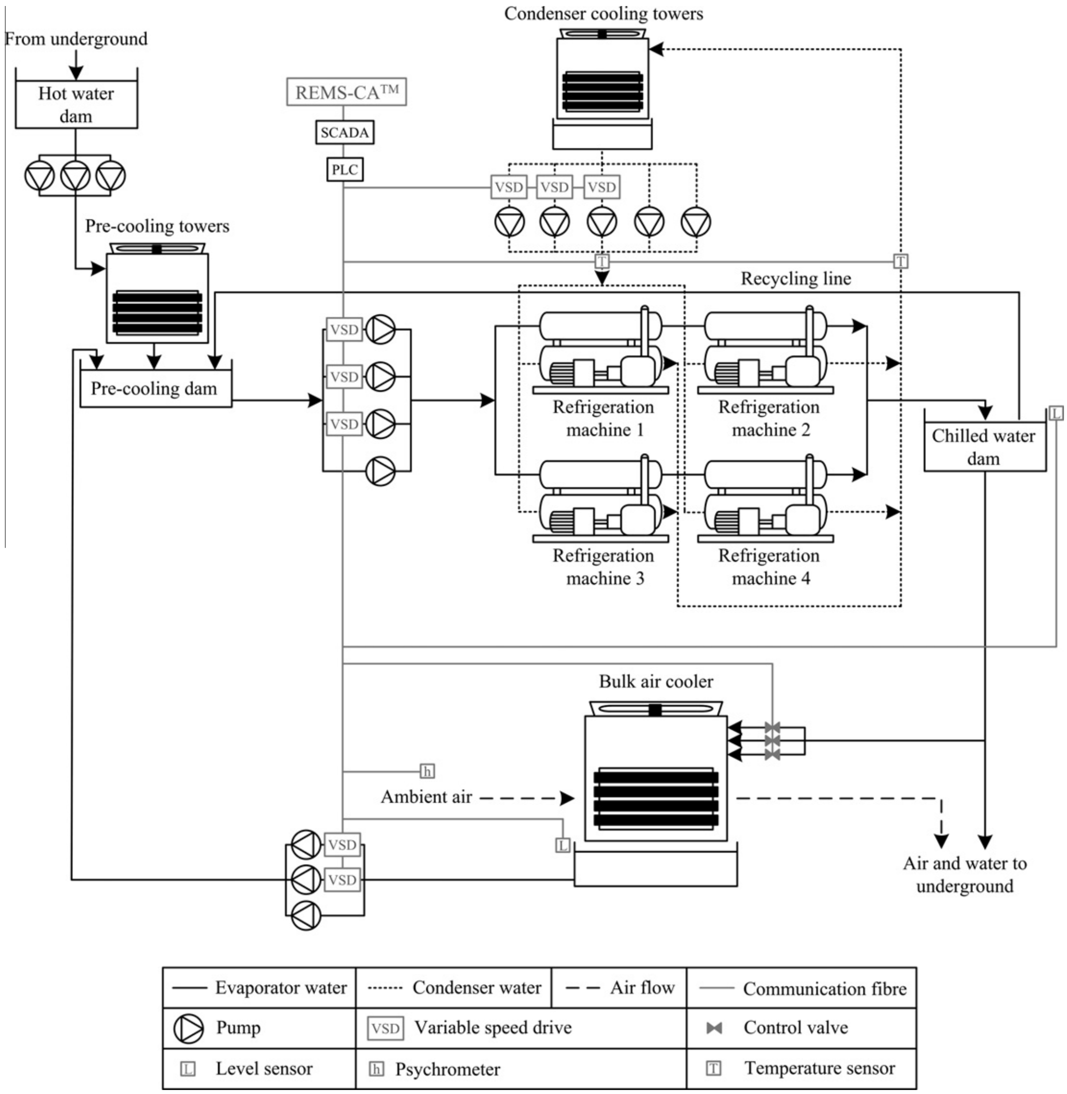

Fig. 1. Kusasalethu surface cooling system layout.

remaining within allowable evaporator water flow rates. VSDs were also fitted to three of the condenser water pumps. These are controlled to maintain the average design water temperature difference across all refrigeration machine condenser lines. Variable condenser water flow is often avoided because of the refrigerant pressure increase and accompanying compressor power increase [15]. However, most mines usually require large condenser pumps. As a result, the pump savings are expected to outweigh compressor power increases. Therefore the combination of these two strategies allows mostly for pump savings at part-load conditions due to the cubic flow–power relation [16].

Control valves were installed in each of the three BAC water supply lines. The valves are controlled according to ambient air enthalpy which is calculated, in real-time, from the ambient pressure and wet- and dry-bulb temperatures, obtained from a compact onsite psychrometer. An air enthalpy increase, at a constant dry-bulb temperature, signifies an increase in relative humidity [9]. More water flow is required and the valves will be commanded to open proportionally. When the enthalpy decreases the reverse process takes place.

This control method allows for ventilation air cooling requirements to be automatically synchronised with changes in ambient conditions. In the process, water usage from the chilled water dam is decreased, resulting in less water to be chilled as well as less water to be pumped back to the pre-cooling dam. Two of the BAC water return pumps were also fitted with VSDs and are controlled to maintain a specified BAC water drainage dam level, presenting further pump savings.

The old pre-cooling towers were replaced with new, more efficient towers. This was done because the cooling of the old towers required recycling of the water from the chilled dam in order to decrease the evaporator inlet water temperature sufficiently. The new towers are efficient enough to deliver water at the required temperature without requiring supplementary water from the chilled water dam. Furthermore, this allows for effective implementation of the strategy to maintain the required chilled water dam level.

In order to implement, control, monitor and report on the outlined strategies, energy management software called Real-Time Energy Management System for Cooling Auxiliaries™ (REMS-CA™) was developed [8]. REMS-CA™ connects to the mine's supervisory control and data acquisition (SCADA) system via the object linking and embedding (OLE) for process control (OPC) standard. The SCADA system communicates with all programmable logic

Table 1
Kusasalethu surface cooling system specifications.

Combined plant	
Hot water dam temperature (°C)	30
Chilled water dam temperature (°C)	6
Chilled water dam level (%)	95
Volume of water sent underground (Ml/day)	27
Combined COP	5
Combined cooling capacity (kW)	42,000
Refrigeration machines (individually)	
Cooling capacity (kW)	13,300
Evaporator outlet temperature (°C)	5.9
Condenser inlet temperature (°C)	18.5
Evaporator water flow rate (l/s)	300
Condenser water flow rate (l/s)	600
COP	6.65
Refrigerant	R134a
Compressor type	Centrifugal
Water pumps	
Evaporator pump motor rating (kW)	90
Number of evaporator pumps	4
Condenser pump motor rating (kW)	185
Number of condenser pumps	5
BAC return pump motor rating (kW)	75
Number of BAC return pumps	3
Cooling towers	
Pre-cooling towers	
Number	8
Water inlet temperature (°C)	28
Water outlet temperature (°C)	24
Air inlet wet-bulb temperature (°C)	7
Condenser cooling towers	
Number	4
Water inlet temperature (°C)	32
Water outlet temperature (°C)	27.5
Air inlet wet-bulb temperature (°C)	22
BACs	
Number	3
Water inlet temperature (°C)	3
Water outlet temperature (°C)	14
Air inlet wet-bulb temperature (°C)	18

controllers (PLCs) of the plant and is used for monitoring and controlling of all mine systems. REMS-CA™ therefore operates interactively by retrieving relevant plant data (such as water temperatures, dam levels and air enthalpy) and sending commands to relevant plant systems such as the required VSD frequencies.

4. Results of implementation

After the energy saving intervention was commissioned, the performance of the system was monitored daily for a period of 1 month with measurements being automatically logged every 2 min by REMS-CA™. The energy savings realised as well as the effects on service delivery and system performance were analysed and the most important results are presented here.

To quantify savings and system influences, principles in *The Measurement and Verification Guideline for Energy Efficiency and Demand-Side Management* (*EEDSM*) *Projects and Programmes* published by Eskom's Corporate Services Division Assurance and Forensic Department, were used [17]. This emphasises the importance of comparing equivalent pre- and post-implementation data. Therefore all condonable data such as mine production shutdowns were disregarded. Only when thermal loads, ambient conditions and other factors relevant to the specific points under discussion were similar, was the data used. Similarly, plant data was used to correctly scale daily pre-implementation power baselines in order to accurately quantify overall savings on a daily basis.

4.1. Energy savings

The energy savings realised could be quantified after modifications to the evaporator, condenser and BAC water flow control and pre-cooling tower replacement. Fig. 2 shows the typical daily power profile of the evaporator water pumps for comparable days before and after implementation of the energy saving intervention. A saving of at least 150 kW can be seen during periods when the evaporator water pumps operated at full load. This is attributed to the base energy saving achieved by modulating all the control valves, previously used for flow control, to the full open position and decreasing pump speeds in order to supply the design flow.

Fig. 2 also shows how the water pump power, which is a function of pump speed, varied during the day when controlled according to water demand in the chilled water dam. Not only are there clear pumping power savings, but there is also a decrease in the refrigeration load and the volume of water which must be chilled daily in order to meet the demand. By controlling the evaporator water pump speeds, the average daily flow rate pumped decreased by 26%, corresponding to a pumping power saving of 66%. In context of the entire strategy, this translates to a 2.8% saving of the combined plant energy usage.

Fig. 3 gives the daily averages of condenser water pumping power required as a function of total condenser water flow rate. The average decrease in daily water flow was 7% while average pumping power decreased by 19%. This is less than the savings achieved by the evaporator pumps because VSDs were applied to a smaller portion of the condenser pump system. Also, the water flow in the condenser system was not as restrictive as in the evaporator system before implementation, giving lower base savings.

However, as previously mentioned, these condenser pumps have large installed power capacities, and a power saving of 173 kW or 2.2% of the combined plant energy usage was achieved. The control method of maintaining an average water temperature difference across the condenser resulted in the daily water flow and power profiles following a similar pattern as shown in Fig. 2. This is because the condenser water flow merely adjusts to the condenser thermal load.

The typical daily power profile of the BAC return water pumps is shown in Fig. 4. This figure illustrates two important results.

First, it can be seen that there is a decrease of at least 80 kW in the full-load pumping power after implementation. Before project implementation water flow was unrestricted. The power savings can therefore be attributed to the decrease in BAC water flow after installation of the water supply control valves. Fig. 4 also shows that the original operation of the BAC and its water supply exceeded cooling demands. This base BAC water flow decrease not only realises return water pump savings as seen in Fig. 4, but also decreases the daily chilled water demand on the refrigeration machines.

The second result shown in Fig. 4 is the fluctuation of BAC return water pumping power in order to maintain a specified BAC water drainage dam level. The average power saving of the BAC pumps was 64%, or 0.9% of the combined plant energy usage. However, the indirect savings realised by decreasing the chilled water demand is of greater significance.

The direct savings realised by installing new pre-cooling towers and by the overall decrease in water chilled by the refrigeration machines are not easily quantified. This is because it is a multiple-input multiple-output problem. However, it was observed that although the recycling of chilled water was no longer required and the BAC return water was reduced, the pre-cooling dam temperature remained constant at about 19 °C. This means that the more efficient operation of the new pre-cooling towers enables the direct supply of colder water to the evaporators. The new pre-cooling towers therefore allow for the decrease in water flow supplied to

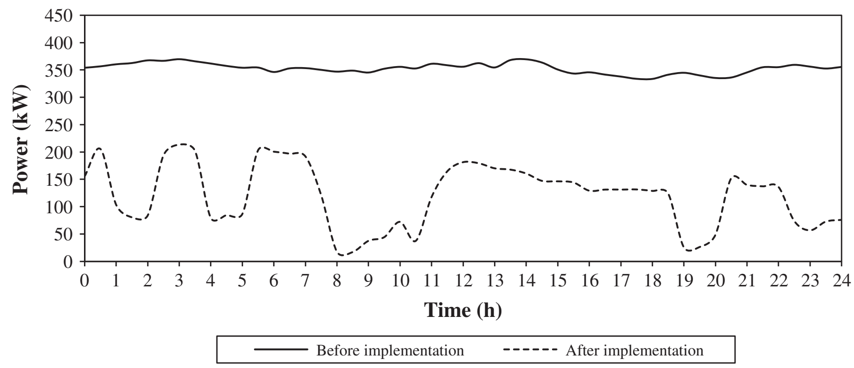

Fig. 2. Typical daily profile of evaporator water pump power.

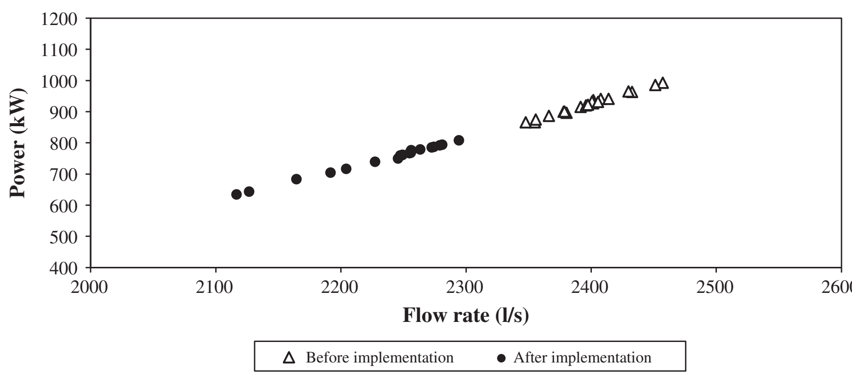

Fig. 3. Daily average condenser pump power as a function of total condenser water flow rate.

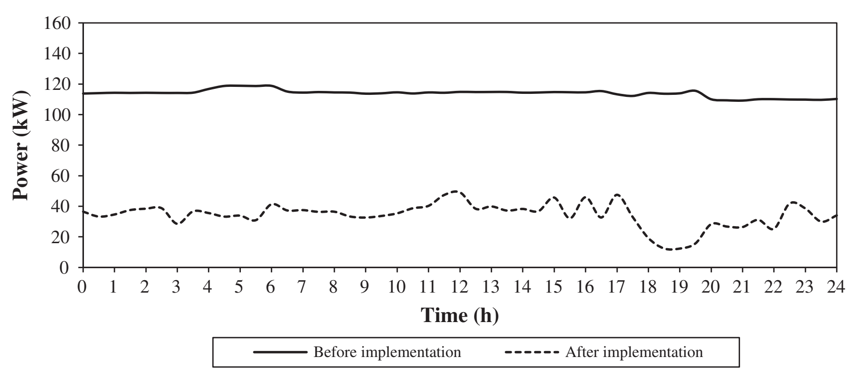

Fig. 4. Typical daily profile of BAC water pump power.

the refrigeration machines and BAC without increasing the inlet temperature and hence the load on the refrigeration machines.

The combined energy savings contributed to pre-cooling tower replacement and chilled water reductions amounted to 25.6% of the combined plant electrical energy usage. The variable water flow strategies not only directly reduce the pump power requirements but, more importantly, result in significant indirect savings by decreasing the daily water volume that must be chilled.

Fig. 5 shows the typical daily profile of the combined cooling plant power usage. The fluctuation in power at part-load conditions can be seen to correspond with that of the evaporator pumps in Fig. 2. The general decrease in overall energy consumption is essentially the consequence of all the modifications already discussed. This includes decreased water pumping power at part- and full-load conditions, decreased refrigeration machine input power at part-load conditions and decreased water volumes chilled by the refrigeration machines due to the new pre-cooling towers, no recycling of chilled water and reduced BAC water supply flow.

The realised average daily saving in combined cooling plant power consumption for the month was 2 521 kW or 31.5% of the pre-implementation power consumption. This saving was measured and verified by an independent auditor. The calculation method was once again based on the Measurement and Verification Guideline [17] and was developed from system data measured by the auditor as follows:

$$\dot{W}_{savings} = \dot{W}_{scaled\ baseline} - \dot{W}_{post\text{-}implementation} \quad (1)$$

where

$$\dot{W}_{scaled\ baseline} = 47.70(T_{amb}) + 603.90(T_{hot\ dam}) - 37.74(T_{chilled\ dam}) + 2.64(\dot{m}_{chilled\ dam}) - 11\ 797.38 \quad (2)$$

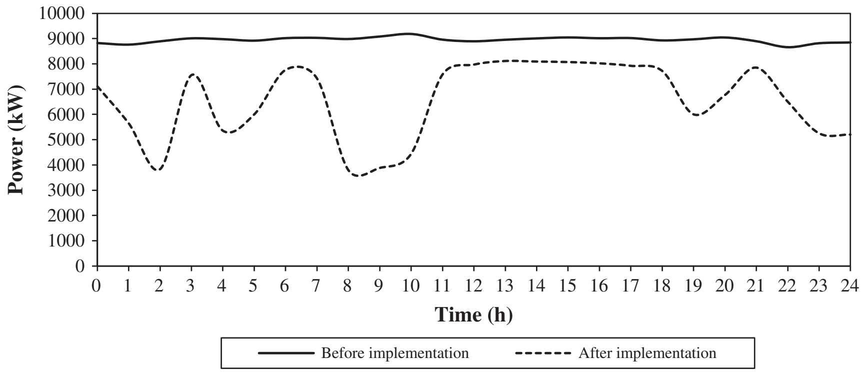

Fig. 5. Typical daily profile of combined cooling system power input.

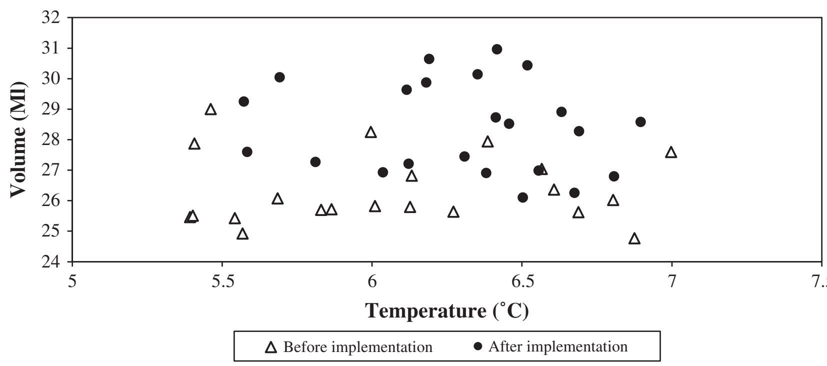

Fig. 6. Daily average chilled water dam temperature and water volume sent underground.

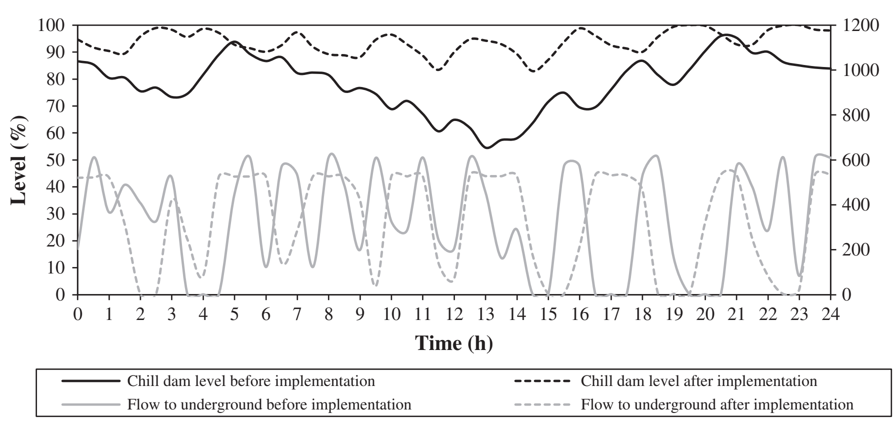

Fig. 7. Typical daily profile of chilled water dam level and flow rate to underground.

Eq. (2) is a suitably accurate regression model that calculates what the daily combined system power consumption would have been had there been no energy saving intervention. The actual power consumption can then be subtracted from this scaled value to determine the daily saving, as shown by Eq. (1). Using a regression model to accurately determine energy savings in cooling systems is a widely used industrial verification method [17,18].

4.2. Service delivery

Fig. 6 shows the daily average chilled water dam temperature and total volume of water sent underground. It can be seen that before implementation of the energy saving strategy the chilled water dam temperature varied between 5.3 °C and 7 °C with a design point of 6 °C. Also, the typical volume of chilled water sent underground varied between 24.5 Ml and 30 Ml per day with a design point of 27 Ml per day. The upper limit of the temperature and lower limit of the volume are the parameters within which the service delivery of the mine must be maintained.

It can be seen in Fig. 6 that the average chilled water dam temperature after implementation of the energy saving strategy remained below the upper limit, averaging at 6.3 °C. This is only a marginal increase in service water temperature resulting from the decreased evaporator flow or decreased BAC usage. The operation of the refrigeration machines was therefore not compromised since outlet water temperatures were maintained by compressor guide vane control [15].

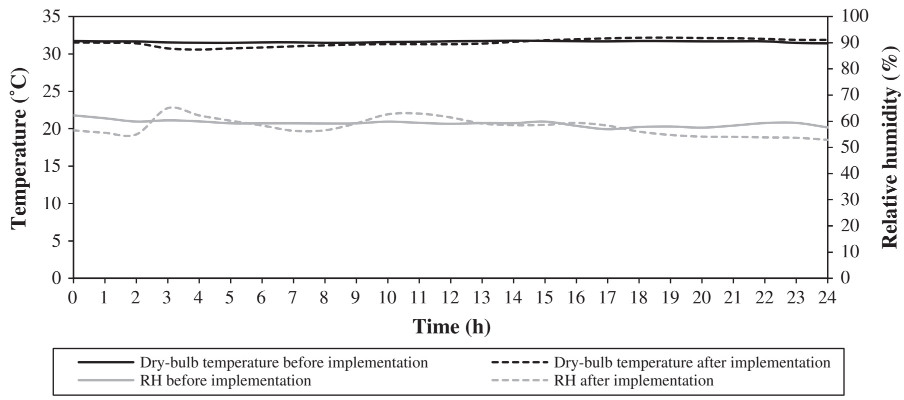

Fig. 8. Dry-bulb temperature and relative humidity at Level 75 BAC inlet.

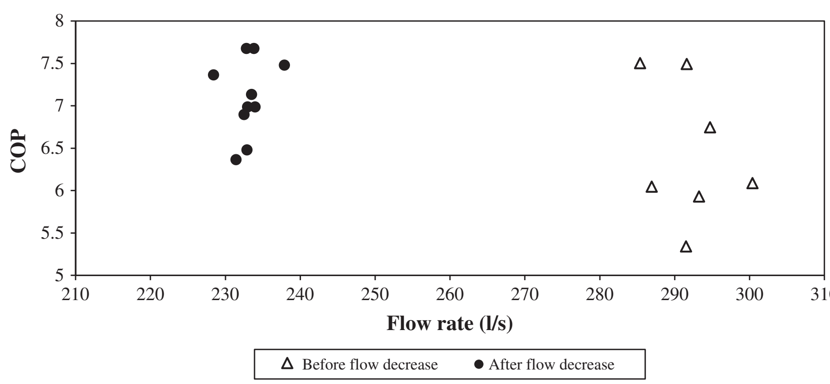

Fig. 9. COP of refrigeration machines 3 and 4 with variable evaporator water flow.

Fig. 6 also shows that the daily volume of water sent underground remained well above the lower limit, indicating that there was no reduction in service water supply as a result of the reduced chilled water supply.

Fig. 7 shows the typical daily profile of the chilled water dam level as well as the water flow rate sent underground. It can be seen that the specified level of 95% was maintained with much less variation than before as a result of the evaporator water flow control philosophy. This means that, because the supply of chilled water is now more accurately matched to the demand, chilled water is more readily available for use underground, thereby improving the service delivery of water availability.

In Fig. 7 the profiles of water flow rate underground are seen to change in two ways, both being advantageous. First, the peaks were reduced from 600 l/s to about 520 l/s. This has beneficial long-term effects such as improved underground control valve performance and less frictional heat increases. Second, the reduced flow rates could be maintained for longer periods. This results in improved valve performance, more constant water supplies and better performance of underground water turbines [9]. Both of these improvements result from the chilled water dam level being synchronised with the underground demand.

Fig. 8 shows the dry-bulb temperature and relative humidity (RH) of the main shaft ventilation air at the inlet of a BAC at underground level 75 before being cooled to the required wet-bulb temperature. The BAC inlet dry-bulb temperature and RH profiles before implementation allowed for sufficient cooling such that the outlet wet-bulb temperature complied with mine ventilation requirements. It can be seen that the effect, after implementing surface BAC flow control, is negligible with an average difference of 2% in RH and 0.5% in dry-bulb temperature. It therefore follows that the ventilation wet-bulb requirement will still be met because of the negligible change in underground BAC inlet conditions. Similar tendencies can be expected in other underground working areas.

4.3. System performance

The separate influences of variable water flow rates on the refrigeration machine performance were evaluated by conducting a series of tests. During one test, the condenser water flow was kept constant at design flow and the evaporator water flow control was applied while all machines operated at full load. The influence on the combined COP of machines 3 and 4 is shown in Fig. 9 where it can be seen that the average COP increased by 10%. Machines 1 and 2 showed similar results.

This effect on the COP is attributed to the compressor capacity control adapting to the cooling load that is influenced by the reduced evaporator water flow rate. The heat transfer in the evaporator is however still effective at this water flow rate. With the condenser coolant being kept at design water flow rate, the relative contributions of evaporator and condenser heat transfer has the cumulative effect of increasing the COP. Evaporator water flow control is thus understandably suggested as an effective method to increase a refrigeration plant COP [11].

Another test was conducted where the evaporator water flow rates were held at the design configuration while decreasing the condenser water flow. The influence on the combined COP of machines 3 and 4 is shown in Fig. 10 where an average decrease of 12% can be seen. This is mainly as a result of the increase in water

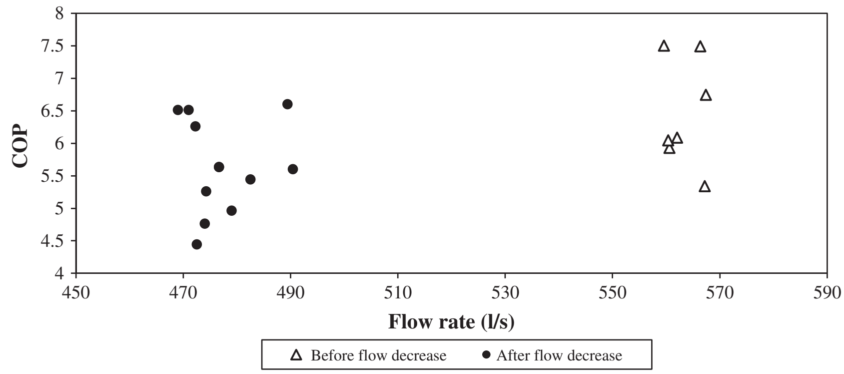

Fig. 10. COP of refrigeration machines 3 and 4 with variable condenser water flow.

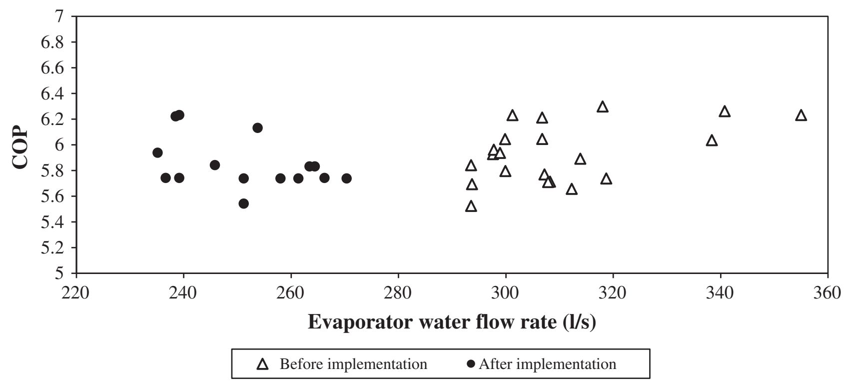

Fig. 11. COP of refrigeration machines 3 and 4 with variable evaporator and condenser water flow.

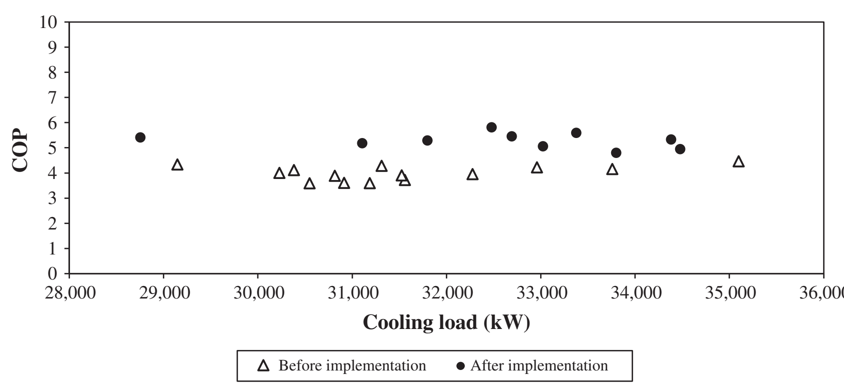

Fig. 12. Daily average COP of combined cooling system.

temperature difference across the condenser in order to cater for the required heat load. This increases the compressor refrigerant discharge pressure and hence the compression ratio required for the same cooling load. The developed energy saving strategy modulates the condenser water flow in proportion to the chiller load by maintaining an appropriate condenser water temperature difference. This ensures that condenser pump savings are realised without degrading the refrigeration machine performance [19].

The collective effect of the evaporator and condenser water flow control on the combined COP of machines 3 and 4 is shown in Fig. 11. It can be seen that although water pump energy savings were realised in both the evaporator and condenser lines, the cooling efficiency of the refrigeration machines was not compromised. The COP was maintained within 1.5% of the original value. It is however important that both the evaporator and condenser water flow control strategies operate simultaneously.

Fig. 12 shows the daily average COP of the combined cooling system as a function of the total plant cooling load. Although the combined cooling loads remained the same, the combined plant COP increased by 33%. This can be attributed to the various refrigeration plant water flow rates being optimally controlled. The overall power consumption of individual components was therefore reduced without compromising the cooling load.

The performance of individual plant components was not compromised as a result of the intervention. All cooling tower supply water pressures were maintained with no noticeable difference in spray patterns or tower fill fouling rates. Pump efficiencies decreased somewhat as a result of the VSD installations, but this

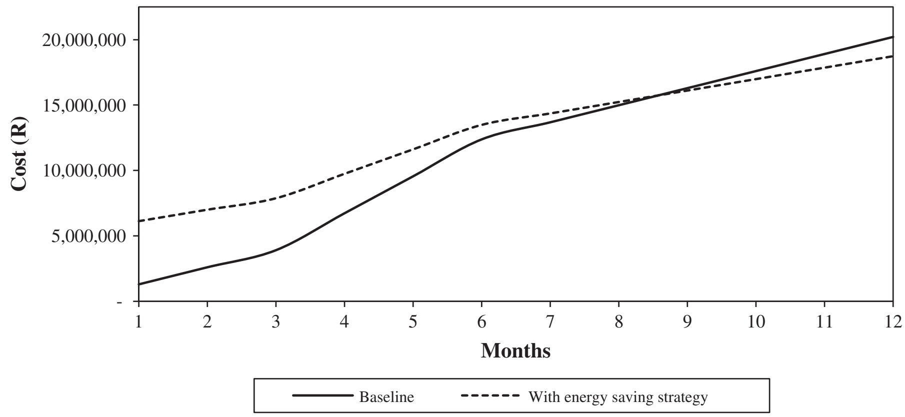

Fig. 13. Total cumulative operating and infrastructure costs of cooling system with and without energy saving strategy ("R" = South African Rand; R1 = US$0.123).

Table 2
Simulated results of strategy application on other deep-mine cooling systems.

	Combined cooling capacity (kW)	Baseline (kW)	Energy saving (%)	Cost saving (*R*)	Payback period (months)
Mine 1	39,000	5,700	25	4,681,243	8
Mine 2	50,000	7,030	18	4,501,536	10
Mine 3	46,000	7,070	21	4,413,889	8
Mine 4	25,500	5,080	23	3,967,912	7
Mine 5	40,000	8,880	14	3,690,742	10

was accepted by the mine when measured against the associated benefits. The evaporator and condenser water flow rates were always maintained above the prescribed minimum values. This prevented refrigeration machine tripping due to laminar water flow causing poor heat transfer and excessive water-side fouling.

4.4. Cost effectiveness

It was shown that the developed strategies can realise significant energy savings without adversely affecting the service delivery or system performance of the cooling system. However, the viability of any energy efficient intervention is also dependent on whether the measure would lead to a benefit that would exceed its cost [20]. A breakeven analysis that demonstrates why the strategy was selected to be implemented at Kusasalethu is shown in Fig. 13.

Fig. 13 shows the forecasted cumulative expenses of the cooling system for one year after strategy implementation. Only electricity costs were included as operating expenses because it was assumed that maintenance and water costs would remain unchanged.

The baseline shows an average monthly operating cost of R1,304,021 during summer months and R2,821,270 during winter months (months 4–6 after strategy implementation). This amounts to an annual cost of R20,200,000. The total infrastructure cost of the energy saving strategy implemented at Kusasalethu is shown to be R5,241,322. The subsequent energy savings translate to an average monthly electricity cost saving of R427,778 for summer months and R950,000 for winter months.

Fig. 13 shows that the payback period of the strategy implemented at Kusasalethu was found to be 8.6 months. After this period, the annual electricity costs would be reduced by R6,700,000 or 33.2%.

The developed energy saving strategy was shown to reduce the annual electricity cost by almost a third of the original value while paying for itself in less than a year. It is therefore reasonable to consider the strategy as a viable and cost effective energy saving intervention. This confirms why the strategy was approved and implemented at Kusasalethu.

5. Further application

All deep South African mines have cooling systems similar in operation and comparable in cooling requirements to the Kusasalethu surface cooling system. The energy saving strategies discussed in this case study can thus be implemented on other mine cooling systems as well. System layouts and specifications are slightly different in each case and therefore the strategy details such as VSD sizes and control limits will be adapted accordingly. However, the basic strategy principles and the integration thereof by means of REMS-CA™ remain unchanged.

Using the same simulation model as before [7], the application of the strategy on a selection of other deep-mine cooling systems was investigated. Summarised results are shown in Table 2.

Table 2 shows that the cooling capacities and average annual baseline power of the selected cooling systems are all comparable to that of Kusasalethu. The simulated average energy savings that would result from implementing the developed strategies vary between 14% and 25% while the annual electricity cost savings are all above R3,500,000. Also, the payback periods are all shown to be less than one year.

The results in Table 2 indicate that it is viable and beneficial to implement the developed strategy on other South African deep mines. This demonstrates the wider potential of the strategy and contextualises the results presented in this case study.

6. Conclusion

Decreasing the energy usage of deep-mine cooling systems is an important demand-side management initiative. It is essential that greater emphasis is placed on optimising cooling load control and energy management, specifically in the mining cooling context. Potential incentives include variable speed refrigerant compressors and further optimisation of BAC flow control.

A newly-developed energy saving strategy based on variable water flow, controlled by REMS-CA™, was successfully implemented at the Kusasalethu gold mine surface cooling plant. The strategy allows the supply of chilled water and ventilation air to be accurately matched to the demand by controlling the components of the integrated mine cooling system in real-time.

The total plant electrical energy consumption was reduced by 31.5%, realising an annual cost saving of R6,700,000 (US$823,100 at present exchange rates). Furthermore, the mine service delivery and system performance was not compromised and the chilled water and ventilation air requirements as well as refrigeration machine COPs were maintained and improved. The strategy was also shown to be cost effective. Comparable simulated results for other sites confirmed the further potential of the strategy.

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Annexure E.1

Improved energy efficiency of South African mine cooling systems

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This article considers and integrates all the facets of the study presented by this thesis in a coherent manner. All chapters and key results are therefore presented and complemented.

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IMPROVED ENERGY EFFICIENCY OF SOUTH AFRICAN MINE COOLING SYSTEMS

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ABSTRACT

Improving the energy efficiency of South African mine cooling systems is an important industrial and national energy sustainability initiative. These energy intensive systems supply chilled water and cold ventilation air to deep mines. An energy audit of 20 cooling systems was conducted and it was found that there is significant potential for energy efficiency improvement. An integrated variable water flow strategy was developed for the specific demands of mine cooling systems. A simulation model was subsequently built and verified to predict the potential impact of the strategy. To integrate and manage the strategy, a real-time, generic energy management tool was developed. In this paper, the development and feasibility of the strategy, simulation model and energy management system are presented. *In situ* experimental results from implementation on four cooling systems with different designs, sizes and requirements are presented as validation of the energy management tool. An average electrical energy saving of 33.3% was realised between all the sites without adversely affecting mine cooling requirements. The paper emphasizes the systems-based approach to energy management of mine cooling systems and its potential large-scale impact on mine sustainability.

Keywords: mine cooling systems, industrial energy efficiency, energy management, variable water flow

1. INTRODUCTION

Energy efficiency improvement of industrial energy systems is of global importance. Industry, including the mining sector, accounts for about 37% of the world's total produced energy **[1]**. The mining industry plays an important role in the South African economy. This sector is energy intensive, accounting for 14% of the national electricity demand **[2]**. In South Africa, mining is therefore a sector in which it is important to consider demand-side management through improved energy efficiency.

Mine cooling systems continuously supply chilled water and cold ventilation air to the mine shaft to ensure acceptable underground operational and working conditions for employees and equipment. These cooling systems are responsible for up to a quarter of the electrical energy consumed at a typical deep level mine **[3]**. Cooling and ventilation is a field in which energy usage can often be optimised or improved by efficient control methods. It is therefore a demand sector that promises strong returns in demand-side management.

Various studies have been conducted regarding electricity and cost reductions on mine cooling systems **[4 - 6]**. However, the focus of previous incentives was on load shifting models and the control of existing equipment. The introduction of modern energy efficient technologies and their integration into specialised energy management systems has not been investigated in the context of mine cooling in South Africa.

An energy audit of 20 mine cooling systems indicated general potential for the large-scale implementation of variable speed drives (VSDs) on mine cooling system auxiliary equipment. A variable water flow control strategy was then developed to implement the VSDs on mine cooling subsystems without affecting mine service delivery or system performance. A simulation model was built, verified and used to predict energy savings that can be attained from the developed strategy. A new generic energy management system was subsequently developed to integrate, control, monitor and report on the developed strategies in real-time **[7]**. The strategy has been implemented on four different cooling systems, one of which has been used as a case study to analyse post-implementation effects on that specific system **[8]**.

This paper presents an overview of the initial energy audit, the energy saving strategy and its simulation model, the new energy management system and *in situ* experimental results from implementation on four cooling systems with different designs, sizes and requirements as validation. The objective is to provide an integrated summary of the various research processes followed in improving the energy efficiency of South African mine cooling systems. Emphasis is on the systems-based approach to energy management of mine cooling systems.

2. ENERGY AUDIT

South African mine cooling systems were evaluated in terms of their typical operation and energy consumption. The aim was to identify the key areas in which energy efficiency can be improved.

2.1 Mine cooling systems

A variety of end-users require chilled water in deep mines. These include bulk cooling of ventilation air, cooling of rock drills and other machinery, rock sweeping operations, dust suppression and underground cooling cars or spot coolers **[9]**. The combined cooling capacity required as a result of these operations is typically 30 MW or more. Large and uniquely designed, integrated cooling systems are required. Such systems are installed on the surface and underground as integral parts of typical semi-closed-loop mine water reticulation systems.

A typical layout of a deep-mine surface cooling system is shown in Figure 1. Hot water is pumped from underground end-users into a surface hot water storage dam, typically at about 30˚C – 35˚C. It is then fed through pre-cooling towers into a pre-cooling dam. These are usually forced draught direct contact heat exchangers that cool the water down to just above ambient temperature **[10]**. The pre-cooled water is then pumped through an arrangement of large water-cooled chillers where the temperature is reduced to approximately 2˚C. The arrangement and size of the chillers depend on the requirements of the specific mine. Chiller cooling water is pumped through a set of condenser cooling towers where heat is transferred to ambient **[11]**.

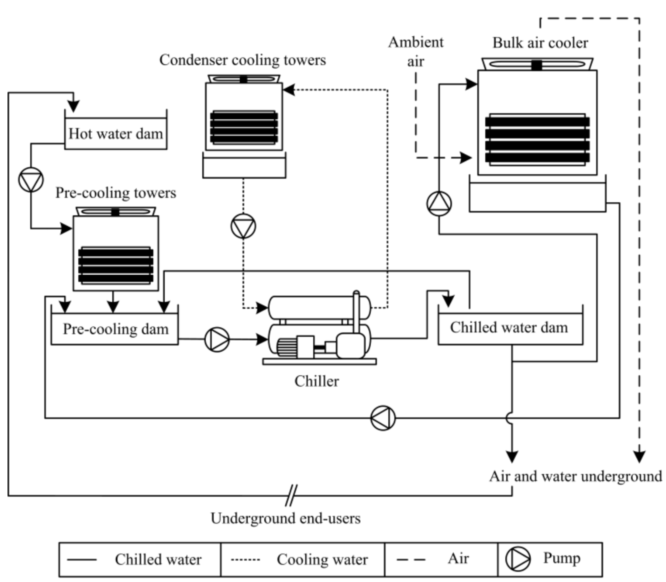

Figure 1 Typical mine cooling system layout

Chilled water is either sent directly to the working face and various underground end-users or pumped through bulk air coolers (BACs). A BAC is an evaporative cooler that cools incoming ambient air to ensure that the legally required underground wet-bulb temperature of 27.5˚C or lower is maintained **[12]**. Used BAC water is usually returned to the pre-cooling dam. Chilled water can also be back-passed as required by specific mine operations.

Demand for chilled water underground is sporadic and relatively unpredictable as a result of the complex network of end-users. The purpose of the hot and chilled water dams is thus to provide storage capacity in the system **[11]**. This ensures that peak water demands can be met while, simultaneously, catering for the fluctuation in water flow requirements.

It is important that an energy efficiency improvement does not adversely affect the mine service delivery requirements and the performance of the various subsystems. It is apparent that effective energy management of mine cooling systems requires the interdependent operation of the subsystems to be collectively and optimally managed as an integrated system.

2.2 Energy consumption

In mine cooling systems, electrical energy input is provided to the chiller compressors and auxiliary equipment such as cooling tower fans, BAC fans, chilled water pumps, cooling water pumps and various transfer water pumps. Thermal energy is transferred from the water in the pre-cooling towers, condenser cooling towers and chiller evaporators. Thermal energy is transferred to the water in the BAC and chiller condensers.

Twenty mine cooling systems were audited to evaluate their specific features, operation and energy consumption. Detailed site visits were conducted to evaluate the systems. Meetings were also held with relevant managers, foremen and operators to obtain further information. Logged system data, typically over a period of one year or more, were obtained from mine personnel. This was used in conjunction with design specification sheets to analyse subsystem loading and energy consumption.

Electrical energy consumed by chillers, pumps and fans were calculated as explained by Saidur et al. **[13]**. The key results of the evaluation are shown in Table 1.

Table 1 shows that 112 large chillers were evaluated. Individual cooling capacities varied between 3 MW and 16.4 MW and coefficient of performance (COP) values varied between 3 and 6.5. Chiller operating hours and loading factors varied somewhat, but the majority of mine chillers operate continuously at relatively high loading factors. Chillers account for 66% of mine cooling system electricity consumption.

Table 1 Electrical energy consumption of selected South African mine cooling systems

	Average	Total
Chillers		
Quantity	4	112
Cooling capacity (kW)	6,563	
Electrical power (kW)	1,257	
Energy consumption (MWh/year)		868,780
Pumps		
Quantity	14	260
Electrical power (kW)	205	
Energy consumption (MWh/year)		353,781
Fans		
Quantity	5	130
Electrical power (kW)	130	
Energy consumption (MWh/year)		95,664
Total energy consumption (MWh/year)		1,318,225

Standard equipment on the audited sites included chilled water pumps, condenser cooling water pumps and various transfer pumps supplying water to pre-cooling towers and BACs. These are low-voltage centrifugal pumps with installed capacities varying between 50 kW and 600 kW. In general, these pumps operate almost continuously at low loading factors and account for 27% of total cooling system electricity consumption.

Axial fans were found to be installed on pre-cooling towers, condenser cooling towers and BACs. Installed capacities varied between 40 kW and 400 kW. Fans comprise only 7% of the total electricity consumption.

A typical mine cooling system uses an average of 4 – 5 chillers, 5 chilled water pumps, 5 cooling water pumps, 4 transfer pumps and 5 cooling tower fans. The average site installed capacity was 10.8 MW and the average annual electricity consumption was 65,911 MWh. The total annual electricity consumption of the evaluated sites was 1,318,225 MWh. This is 4.0% of the total electrical energy used by all mines in South Africa and 0.6% of the total national electricity supply.

2.3 Saving potential

It was found that most cooling systems operated at predetermined chilled water flow rates. These flow rates are regulated by the inefficient throttling of control valves. When the chilled water dam is full, the water is returned to the pre-cooling dam until the chilled water is required underground or for bulk air cooling. It is also not unusual 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. The supply of sufficient water at a specified temperature is easily achieved by existing operational and control components of deep-mine cooling systems. However, it was found that the supply often exceeded the demand without taking into account optimal and energy efficient equipment operations.

Loading and scheduling operations were observed to be generally inefficient on mine cooling systems. Most motors are oversized and operate at low loading factors and chillers are not operated optimally for given loading conditions. Furthermore, part-load conditions were identified on all systems. This was primarily due to daily ambient condition fluctuations and the intermittent nature of water usage underground.

No VSDs were installed on any of the electric motors of the mine cooling systems. These mines comprise about 80% of deep mines in South Africa. In most cases, it was found that the lack of VSD acceptance was due to a general lack of awareness and initiative. It is believed that this can be attributed 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. This appears to still be the case among most technical personnel.

Studies have shown that using variable speed electric motors is one of the most efficient and promising methods of utilising part-load conditions to realise energy savings **[14]**. For example, the increased frictional resistance and pressure drop as a result of valve control can be eliminated or reduced significantly 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 cubic power-flow affinity law **[15]**.

From the observations regarding inefficient operations and part-load conditions it was apparent that there should be significant potential for implementing VSDs on mine cooling systems. In South Africa, all mine chillers have medium-voltage power supplies. Medium-voltage VSDs have not yet been widely introduced in the country and are also comparatively expensive at present. It was therefore proposed that VSDs should be widely installed on the next largest cooling system energy consumer, namely water pumps.

3. ENERGY EFFICIENCY STRATEGY AND SIMULATION

To optimally implement VSDs on mine cooling system water pumps, it is necessary to control them according to energy efficient strategies specifically developed for the unique demands of mine cooling systems. It is also necessary to simulate the cooling systems with and without the VSDs to predict the potential savings before implementation.

3.1 Variable water flow strategies

Variable speed energy efficiency strategies have been investigated in various studies. A variable speed pumping scheme was investigated for an academic building chiller system by Tirmizi et al., realising energy savings of up to 13% **[16]**. Crowther and Furlong showed how variable speed cooling tower fans can also save energy **[17]**. Qureshi and Tassou confirmed that capacity modulation by applying VSDs to chiller compressors can lead to 12% - 24% energy savings **[18]**. Energy savings of 19.7% were presented by Yu and Chan for all-variable speed chiller systems **[19]**.

Mine cooling subsystems that were identified as the main systems using energy-intensive pumps are the chiller evaporator, chiller condenser and BAC. The developed variable water flow strategies therefore involve modulating the water flows through these systems according to their specific part-load conditions while adhering to their specific constraints. Figure 2 schematically shows the three variable water flow strategies.

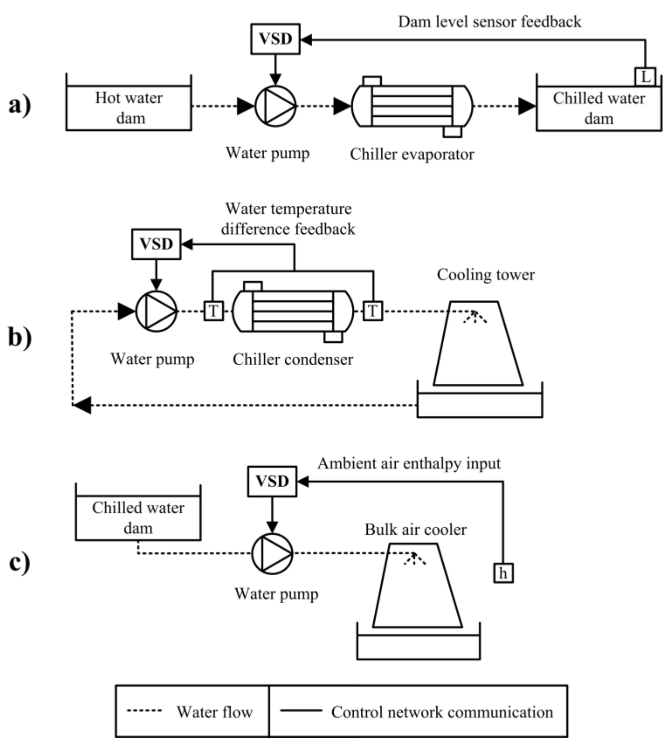

Figure 2 Variable water flow strategies for the evaporator (a), condenser (b) and BAC (c) water lines

The mine constraints placed on the evaporator water line are the requirements for a specific chilled water temperature that will be available in the chilled water dam on demand. The evaporator flow strategy involves the chilled water flow rate to be controlled by means of a VSD installed on the pump. As shown in Figure 2(a), the evaporator VSD is controlled by a proportional-integral-derivative (PID) loop using the desired chilled water dam level as set point. The water flow rate is not to be decreased below about 60% of the design flow speed because transition into the laminar flow region occurs, reducing heat transfer and increasing water-side fouling. This will result in a decrease of the plant COP **[20]**.

Back-passing of chilled water dam-overflow to the pre-cooling dam is eliminated by the control strategy, enabling the water flow rate to be reduced below design conditions during times of low demand. The average evaporator water inlet temperature increases because no recycled chilled water is available to lower the average pre-cooling dam temperature. As compressor capacity control maintains a fixed water outlet temperature, the water temperature difference across the heat exchanger increases **[21]**. It follows that the water flow can be reduced and pump savings realised without adversely affecting the cooling load.

The constraints on the condenser water flow are the condenser cooling tower limitations and the chiller cooling load. Most manufacturers warn against constantly decreasing the water flow below the design point since, for a constant cooling load, the water temperature difference across the condenser will increase. This results in an increased compressor discharge pressure which increases energy usage and lowers the COP at partial load conditions **[21]**.

The preferred strategy is to adapt to the changing chiller load by maintaining the set point design condenser temperature difference when varying the water flow, as shown in Figure 2(b). The condenser water flow rate is also controlled by means of a PID control loop.

In typical BAC operations, off-design ambient conditions are commonly encountered and BACs usually supply ventilation air at wet-bulb temperatures much lower than actually required. As shown in Figure 2(c), the BAC flow control strategy involves the modulation of the BAC supply water flow rate in proportion to the ambient conditions in order to meet the mine ventilation air demands. A feed-forward control strategy controls the flow rate by using ambient enthalpy as input. The air enthalpy is calculated in real-time, using air pressure and wet- and dry-bulb temperatures, obtained from a compact digital psychrometer.

Although BAC water pump savings are also realised, the primary energy saving comes from the reduction in the chilled water demand. The extent of the saving depends on ambient conditions, but significant reductions will be realised in the daily amount of water to be chilled.

Most cooling tower manufacturers warn against reducing the water flow below about 80% of the design point (using conventional fixed-orifice nozzles) since this results in uneven fill wetting and thus reduces cooling tower performance and increases rates of scaling **[22]**. This is taken into account during the commissioning of strategies

(b) and (c) by incorporating the lower flow and pressure limits at which fill wetting and evaporative cooling is still efficient for each specific cooling tower or BAC system.

Manually-operated throttling valves should be opened fully for all three strategies to be effective. Subsequent modulation of flows to design points alone present a base energy saving as a result of the cubic power-flow relation.

The variable water flow strategies are therefore aimed at realising pump as well as chiller savings by utilising part-load conditions to reduce the water flow rates and daily volumes to be chilled. Mine chilled water and ventilation air demands will be met without oversupply.

3.2 Strategy simulation

The developed energy saving strategy was simulated in order to evaluate its potential energy and cost savings. Although the performance of mine chillers have previously been simulated **[23]**, no commercially available packages exist that simulate integrated mine cooling systems.

An integrated, dynamic, component-based simulation model was developed which balances energy and mass over defined time intervals. Provision was made for hourly inputs over a period of 365 days, or 1 year, in order to reflect daily and seasonal changes in system boundaries.

Inputs are provided in the form of hourly ambient conditions, hourly mine demands of chilled water and system parameters such as dam capacities, chiller, BAC, pre-cooling tower, condenser cooling tower, water pump and PID controller specifications. Output of the simulation is given as the performance of the integrated system, including the combined power usage.

The mathematical models used in the simulation are based on thermodynamic and physical properties of the system as adapted for large thermal system simulations by Arndt **[24]**.

To verify the accuracy of the developed simulation model, the baseline performance of a mine surface cooling system (mine A) was simulated using historic data as input (before any energy saving interventions). Simulation results were then compared to the actual performance over the same period, which was during a summer month. The average daily profile of the simulated and actual electrical power usage of the combined cooling system for the summer month under consideration is shown in Figure 3.

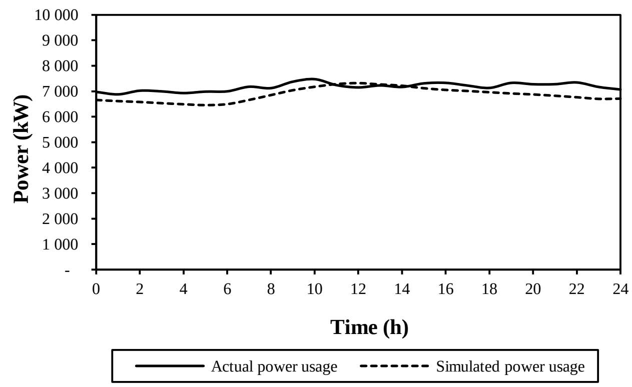

Figure 3 Average daily profile of simulated and actual cooling system power usage for mine A (one summer month)

It can be seen in Figure 3 that the simulation closely follows the actual power profile with an average accuracy of 4.1%. The verification process was repeated for 12 months of the year and an overall average accuracy of 7% was achieved. Given that the design, operation and schedules of the actual system are the same as used in the simulation, the model can be assumed to predict the overall system energy performance with an acceptable level of accuracy. The developed simulation model is therefore a viable tool to investigate the energy saving potential of the developed strategies on mine cooling systems.

The simulation model was used to calculate the potential savings that could be realised from the newly-developed strategy. The electrical energy usage over a period of one year was simulated for four different mine cooling systems using logged mine data as input. This was done for the existing systems and for the case when implementing variable speed drives and controlling them according to the proposed strategies. A summary of the annualised simulated results is shown in Table 2.

Table 2 Simulated electrical energy savings for the cooling systems of mines A – D

	Combined cooling capacity (kW)	Simulated electricity baseline(kW)	Simulated electrical energy saving (%)
Mine A	42,000	5,399	33
Mine B	39,000	5,700	25
Mine C	50,000	7,030	18
Mine D	46,000	7,070	21

Table 2 shows that the simulated average energy savings that would result from implementing the developed strategies vary between 21% and 33%. At the time of simulation, the proposed annual electricity cost savings were all above US$250,000 and the payback periods were all shown to be less than 13 months. The verified simulation model therefore indicated that the newly developed energy saving strategies have the potential to realise significant energy and cost savings on a variety of deep-mine cooling systems.

4. INTEGRATED ENERGY MANAGEMENT SYSTEM

The energy saving strategies that were developed and simulated needed to be implemented by a practical energy management tool. This tool must integrate all the strategies generically for any mine cooling system, and monitor and report actively on the energy usage in real-time.

Centralised energy management systems have gained popularity in contributing to continuous energy management systems such as heating, ventilation and air-conditioning (HVAC) systems **[25]**. Investigations to optimise control and energy management systems of mine ventilation systems have also been made **[26, 27]**. However, the majority of these systems do not simultaneously address the concerns of operational efficiency, control robustness and computational costs.

There is therefore a requirement for simple, integrated energy management methods that provide remote control and real-time energy consumption monitoring **[28]**. Such methods have been presented for building systems by Marinakis et al. **[29]**. The advancement of such systems is currently not developed to the same degree in industrial processes that are often more energy intensive **[30]**.

An energy management system called Real-time Energy Management System for Cooling Auxiliaries (REMS-CA™) was developed as a central energy managing tool for large mine cooling systems **[31]**. The focus of the tool is a generic systems approach to energy efficiency and integrated energy management. Features include a robust supervisory and functional specification, a simple optimisation and hierarchical control system, an automatic reporting system and an easy-to-use interactive monitoring platform. A summary of the functionality is given here while more detail is given by Du Plessis et al. **[7]**.

4.1 Functional specification

The energy management system integrates with existing mine communication networks as a hierarchical cascade controller, as shown in Figure 4 **[7]**. This system architecture involves inner control loops managed by a network of local programmable logic controllers (PLCs) and an outer control loop managed by a central supervisory, control and data acquisition (SCADA) system. This ensures complete control and monitoring of the entire PLC network and is therefore a popular approach to data acquisition and centralised energy management **[32]**.

The REMS-CA™ server communicates with the mine SCADA client via the OPC protocol (Object linking and embedding for Process Control). This protocol ensures the real-time exchange of data between two independent platforms. The OPC connection enables the system to be integrated to any mine SCADA and thereby ensures a generic energy management tool.

The energy management system server is accessed through an interactive user interface, usually viewed from a personal computer (PC). This allows the user to monitor and control the energy management system in conjunction with the existing SCADA system.

After the system has been customised for a specific cooling system via a user friendly visual editor suite, preferences can be provided on the user interface. Such preferences typically include allowable control limits of equipment and specific subsystem set points to ensure that service delivery requirements are met. The high-level functional outputs of the energy management system are real-time monitoring of energy usage and all system parameters, real-time optimisation and control of subsystem and auxiliary equipment and the automatic daily, weekly and monthly reporting of energy consumption and its management.

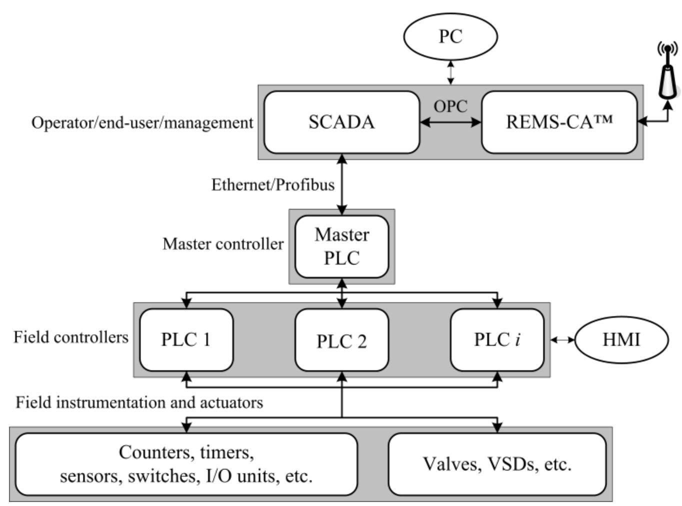

Figure 4 Integrated energy management system architecture **[7]**

Various control loop options are specified in the system such that control will never be relinquished. This is to ensure redundancy and practicality on mine cooling systems. The control capability of the energy management system enables the control of the subsystems and auxiliary equipment to optimise the electrical energy consumption of the integrated cooling system through generic control functions as described in section 3.1. This is done as simple as possible to minimise computational time and costs and to improve the service, upgradeability and maintenance of the system long after implementation.

The developed energy management system therefore allows for simple control and optimisation of each controlled subsystem while taking into account the real-time interaction with other subsystems. An advantage of the outer-loop controller functions in the energy management system is that a large number of subsystems can be optimally controlled in an integrated manner without increased computational cost. Furthermore, the generic design of the controllers allows adaptability to various mine cooling system layouts. Electrical energy of integrated cooling systems on different sites can thus be optimally managed in real-time by using the same basic energy management tool, customised for each individual plant.

4.2 Monitoring and reporting

A real-time supervisory monitoring functionality supports the control tools to achieve integrated energy management. This is made available as a separate tab in the REMS-CA^{TM} platform with various monitoring, statistical and graphical display tools available to the user. Typical examples include the graphical tracking of daily power consumption of the overall cooling system or its subsystems, tracking of critical system parameters such as dam levels or temperatures and the real-time calculation of cost savings realised by the management system. An automatic alarm system can also be set up to alert the user to abnormal energy usage, system performance or network-related issues. Figure 5 is an example of a customised monitoring page in the system platform **[7]**.

Figure 5 Example of an energy monitoring page in the energy management system **[7]**

An automatic reporting and data backup capability supplements the monitoring function of REMS-CA^{TM}. This system uses logged plant and power data to automatically create a customised document reporting the energy usage, energy and cost savings, measured against pre-determined baselines, as well as recommended areas for improvement in the operation of the integrated cooling system. These reports are created on a daily, weekly and monthly basis. All reports, alarms and recommendations are available on the system itself or automatically sent via e-mail or mobile phone text messages.

Local mine networks are typically connected to display monitors both at the plant and at the central control room of the mine. As shown in Figure 4, a wireless router further enables the remote connection to external locations such as the control rooms of the Energy Services Company (ESCo) responsible for implementation, mine group energy management, or electricity supply utility. The system enables the real-time monitoring function and usage reports to be available to an integrated network of interested parties. This ensures complete energy management by means of a top-down approach since energy-conscious performance is typically of increased concern at managerial level.

5. EXPERIMENTAL VALIDATION

The developed variable flow strategies were implemented on four different South African mine cooling systems through the installation of the required equipment and REMS-CA^{TM}. Important *in situ* experimental results from each of the sites are presented here to investigate the feasibility and validity of the developed energy efficiency initiative. Only key results regarding energy savings, service delivery and system performance are shown. More detail is given by Du Plessis et al. **[7, 8]**.

Accurate measurement of data and energy savings from industrial energy efficiency projects can alleviate any uncertainty about the efficacy of such projects and improve future estimates of expected savings on similar systems **[33]**. Therefore, principles discussed by Xia and Zhang **[34]** are followed to verify energy saving results. These principles conform to the measurement and verification specifications for energy saving projects given by the South African Bureau of Standards **[35]**. Suitable scaling parameters were also identified for each site by an independent auditor and used to accurately calculate realised energy savings.

Table 3 gives a summary of the studied cooling systems and the key results that were obtained. The system layouts varied significantly, encompassing the majority of cooling system layouts found in South African mines. They included a system with a combination of parallel and series chillers (mine A), a parallel chiller system (mine B), a system with an intermediate chilled water dam between chillers (mine C) and a closed-loop BAC system (mine D).

Table 3 Experimental results summary of mines A - D

	Mine A	Mine B	Mine C	Mine D
Performance assessment duration (months)	3	3	2	2
Average electrical energy saving (kW)	2,609	1,865	606	1,149
Average electrical energy saving (%)	35.4	31.7	29.3	33.8
Annual cost saving (US$)	1,095,611	784,036	254,925	482,658
Payback period (months)	7	10	17	5
Average daily temperature (˚C)	Water: 6.0 (before) 6.4 (after)	Water: 3.8 (before) 4.3 (after)	Water: 7.3 (before) 6.6 (after)	Air: 7.4 (before) 7.9 (after)
Chilled water volume used (Ml/day)	27 (before) 27.4 (after)	17.5 (before) 16.3 (after)	11.9 (before) 12.6 (after)	-
Average system COP	4.5 (before) 6.1 (after)	5.2 (before) 6.9 (after)	4.2 (before) 6.2 (after)	4.8 (before) 6.4 (after)

It can be seen in Table 3 that the energy savings realised on all sites were significant, averaging at 33.3%. As an example, the daily average power consumption of the combined cooling system of mine B is shown in Figure 6 **[7]**. It is shown that, with the exception of 8 days, positive net savings were reported on a daily basis for the integrated system. Variation in daily savings can be expected as shown because factors such as ambient conditions, mine water demands and inlet temperatures all influence the daily cooling demand. The extent to which auxiliary equipment and chiller loading can be optimised therefore depends on daily requirements.

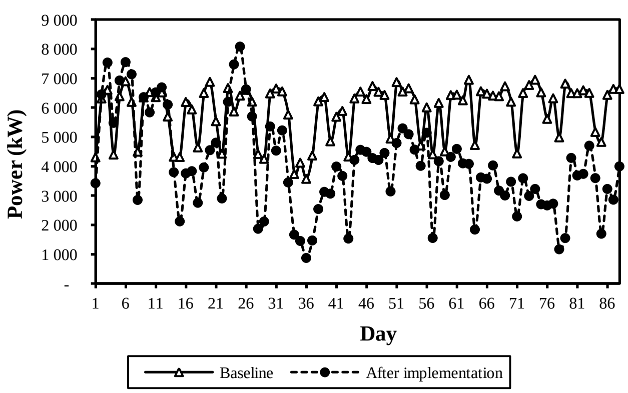

Figure 6 Daily average power consumption (mine B) **[7]**

The realised savings are shown to be higher than the simulated 24.3% shown in Table 2. This is because the simulation was averaged over a year while the *in situ* results are only for three months. Seasonal effects strongly influence the savings that can be realised in cooling systems.

Table 3 indicates that the strategy does not greatly affect chilled water and ventilation air temperatures. In most cases the water temperatures increased slightly. This is attributed to the new control method of maintaining a set dam level, thus requiring a large volume of water to remain in the dam for long periods. However, all temperatures after implementation were well below the limits accepted by the mines. It is apparent that chiller capacity controls functioned as designed by maintaining the set point outlet temperature for varying water flow rates, given that the flow rates are within limits allowed by the machine.

It is shown in Table 3 that the daily chilled water volumes used did not fluctuate significantly. This indicates that the availability of chilled water to the end-users was not affected by the strategy.

Figure 7 **[7]** shows that although the combined cooling loads of mine A remained within the same range, the system COP increased by 36%. This result indicates that the cooling load of the entire plant, or the overall service delivery, was not compromised while the total electrical energy consumption was significantly reduced. The COP is shown to be similar before and after implementation for very high thermal loads. This is to be expected because days of high thermal demand will require higher electrical energy input with less scope for optimisation. This means that, as the loading on the system decreases, the potential for the central energy management system to realise part-load savings by matching the water supply to the demand increases. Similar trends in the system COP can be seen for the other sites, as shown in Table 3.

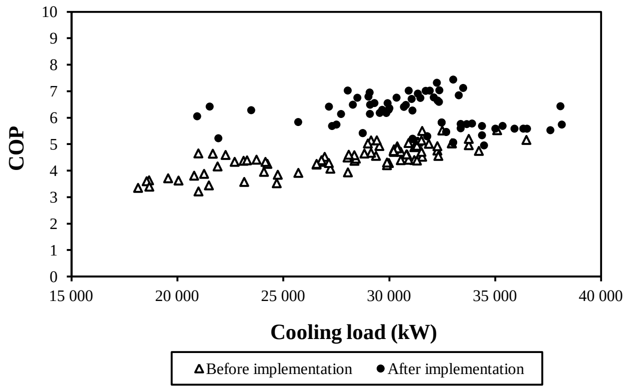

Figure 7 Daily average system COP (mine A) **[7]**

An energy management solution will only be viable for implementation and further consideration if it is economically feasible. Equipment costs include new VSD installations, control valves, measurement instrumentation and additional equipment such as power and instrumentation cables. System integration costs include software costs, PLC and SCADA alterations to enable the new energy management system to function as specified.

Table 3 shows that the payback periods for all the sites were found to be less than two years. This generally indicates good viability for an energy management system, particularly when similar technological features are involved **[36]**. It can therefore be concluded that the payback period analysis of the four sites on which the new energy management system were implemented indicates that the system is economically feasible.

6. CONCLUSIONS

South African mine cooling systems are energy intensive and it is important to improve their energy efficiency. Various load management efforts have been made, but large-scale energy efficiency improvement by integrated energy management still needs further development.

An energy audit of 20 mine cooling systems indicated that these systems account for 4% of the total electricity consumed by South African mines. Inefficient practices such as chilled water recirculation showed that there is potential to install VSDs on the water pumps of these systems.

An energy saving strategy was developed to integrate VSDs on mine cooling subsystems. The strategy comprises the control of chilled water, cooling water and BAC water flow rates.

A simulation model was built, verified and used to predict energy savings that can be attained from the developed strategy. Simulated results of four mine cooling systems indicated an average annual saving of 24.3%, attributed to pump savings and chiller savings resulting from matching chilled water supplies with its demand.

A new generic energy management system was developed to integrate, control, monitor and report on the developed strategies in real-time. The system connects to mine SCADA systems and features a hierarchical control system. A real-time monitoring, alarming and reporting function connects to various interested stakeholders and supports the integrated energy management objective.

In situ results from four large cooling system applications with different layouts were considered as experimental validation. It was shown that an average electrical energy saving of 33.3% was realised for all the sites. Mine service delivery requirements were also never adversely affected. The average payback period was shown to be 10 months.

It can be concluded that the developed strategies and energy management system improved the average energy efficiency of the mine cooling systems under consideration without reducing its performance or service delivery. It is apparent that there is significant potential for the future development of systems that manage the energy usage of mine cooling systems by an integrated systems approach.

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Annexure E.2

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