CHAPTER 8. VALIDATION OF DEVELOPED ENERGY SAVING STRATEGY

8.1 Introduction

A new variable water flow DSM strategy has been proposed and a new energy management system to implement it has been discussed. The Kusasalethu surface cooling system has been identified as the primary case study. The energy saving and economic viability of the developed strategy has been demonstrated by means of a feasibility investigation on the case study site. The implementation details of equipment, the energy management system and verification procedures for the case study have subsequently been presented. This chapter proceeds by validating the new DSM strategy through verified *in situ* experimental results.

The electrical energy savings are discussed first with specific reference to the evaporator, condenser and BAC pumps as well as the combined system electrical energy usage. The influence of the strategies on service delivery is then presented by comparing equivalent pre- and post-implementation measurements of chilled water and ventilation air. Similarly, the effects of the strategies on system performance are also investigated by the comparison of various relevant subsystems and their parameters. Finally, conclusions are drawn regarding the validity, feasibility and success of the integrated strategy as a novel energy saving method for large cooling systems.

The article presented in Annexure D.1 (Du Plessis et al. 2013a) is based on the key results of this chapter. This chapter provides additional details and results to give the full scope of the experimental investigation. The time period used to log post-implementation data was the DSM project performance assessment period of three months (March to May 2012). However, at the time the article was compiled, only the data for March had been logged. Although there are slight discrepancies because the results in this chapter are based on a larger set of data, it is shown that the two sets of key results are acceptably similar.

8.2 Energy savings

To evaluate the success of the DSM intervention it is necessary to first evaluate the energy savings realised. The pump savings realised by the evaporator, condenser and BAC return pumps are evaluated separately before considering the energy savings of the combined cooling system, including the energy usage of all auxiliary equipment and chillers.

In Chapter 6.4 the verified simulation model predicted that the developed strategies have the potential to realise electrical power savings of 1 779 kW (33% of the simulated baseline power usage) at the Kusasalethu surface cooling system, based on the system data of 2009. Since 2009 the system power usage has increased by about 2 MW as per Figure 76. Insufficient system data was available to run complete simulation models for more recent years. It is believed that the percentage savings should remain similar to the predicted percentage savings for the increased cooling demand and associated power increases. Based on the simulated results and an added safety factor, the average annual target saving of the implemented DSM project was set at 1.5 MW (1.6 MW in summer and 1.2 MW in winter).

8.2.1 Evaporator pumps

First, the effect of the new strategy and energy management system on the energy performance of the evaporator pumps was investigated. For simplicity, the water flow rates and electrical power input values were considered for the evaporator pump group as a whole. Only comparable data sets before and after implementation were considered, in accordance with standard measurement and verification procedures as discussed previously (Eskom Corporate Services Division 2011). The evaporator pump electrical energy savings realised by implementing the proposed evaporator water flow control strategy are shown in Figures 77 to 79.

Figure 77 shows the daily average evaporator pumping power input and evaporator water flow rate before and after implementation of the strategy.

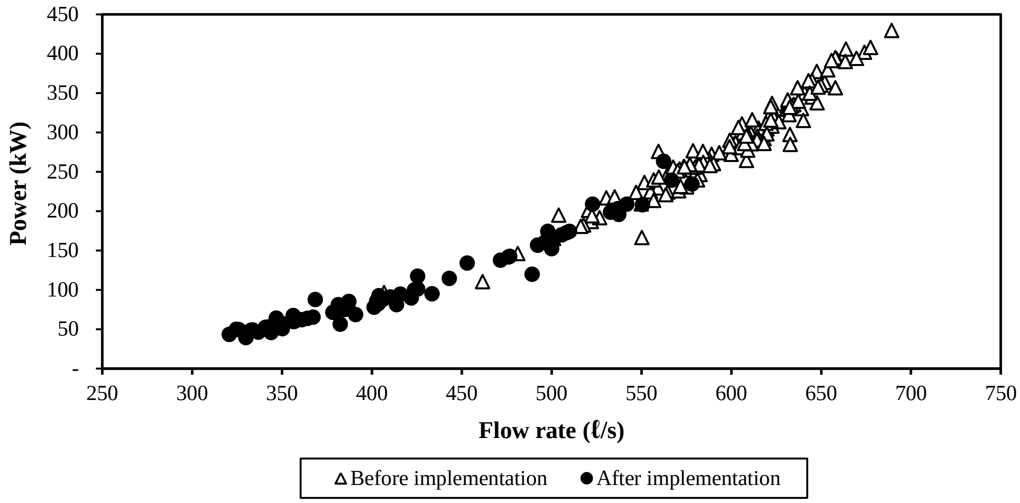

Figure 77 Daily average evaporator pump power as a function of total evaporator water flow rate (Kusasalethu)

Figure 77 indicates a significant reduction in both the water flow rate and associated power input of the evaporator pump group. The daily flow rate decreased by an average of 27%, while the power input decreased by 69%. This translates to a power saving of 177 kW, or 6.7% of the combined cooling system savings. Relative to the pre-implementation energy usage of the combined system, this strategy alone represents a 2.4% saving. The flow and power savings differ slightly from those reported in Annexure D.1 (26% and 66% respectively).

The reduction is attributed to the cubic relation between flow and associated power input, as clearly shown by the trend in Figure 77. The post-implementation evaporator flow rates were modulated continuously to match the chilled water demand while staying within equipment constraints, as proposed by the strategy of maintaining the chilled water dam level constant. This shows the extent to which chilled water was oversupplied by recirculation before strategy implementation.

The overlapping of pre- and post-implementation data points is ascribed to the fact that neither the pre-implementation scheduling of pumps nor the underground chilled water demands are kept constant on the Kusasalethu mine. It can therefore be expected that there will be variation from the average values.

The average daily profiles of the evaporator pump group before and after strategy implementation are shown in Figure 78.

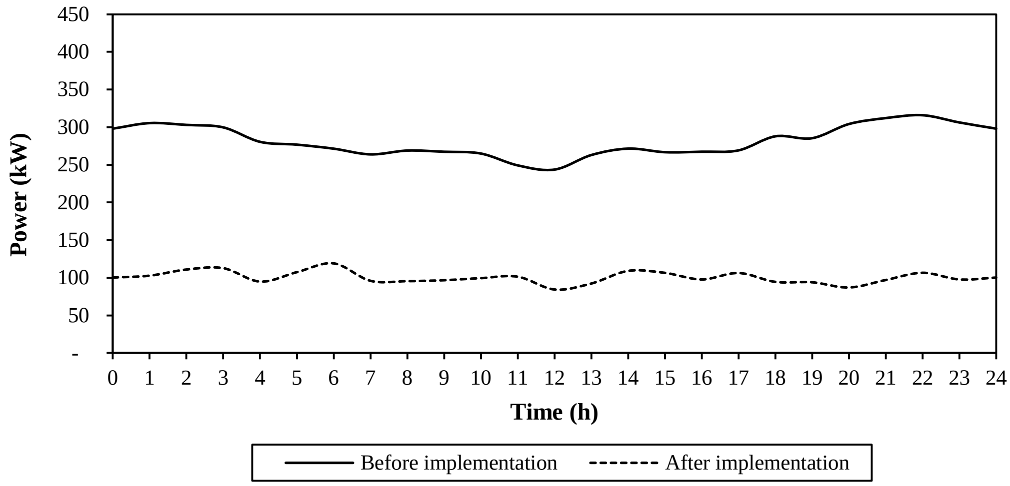

Figure 78 Average daily profile of evaporator pump power (Kusasalethu)

It can be seen in Figure 78 that after implementation the evaporator pump group used only about a third of its original electrical power input, as confirmed by the preceding discussion. The power profiles are shown to be relatively constant because they are averaged over periods of about three months in each case. This confirms that the flow control and pump scheduling profiles were not the same every day.

To investigate the daily effects of the evaporator flow control strategy, comparable typical daily profiles of pre- and post-implementation sample days are shown in Figure 79 (Du Plessis et al. 2013a).

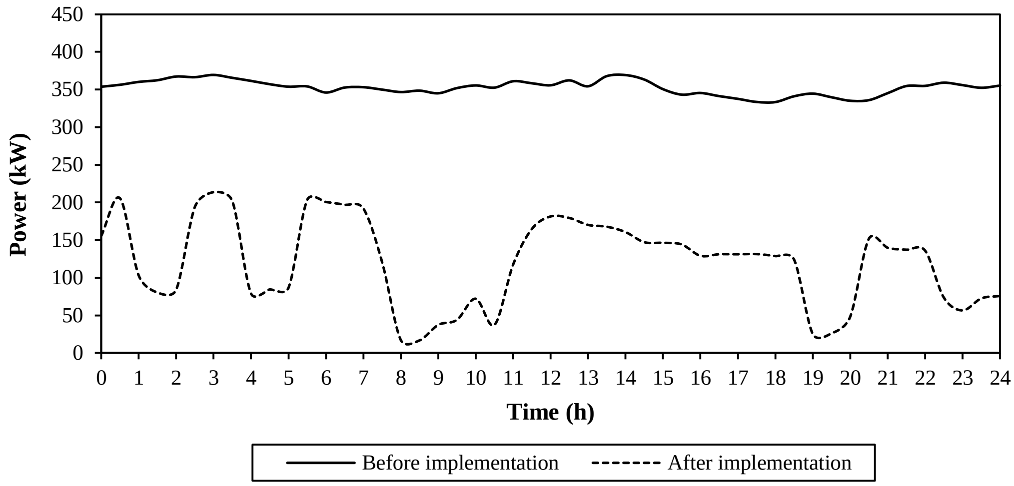

Figure 79 Typical daily profile of evaporator pump power (Kusasalethu) (Reprinted from *Case study: The effects of a variable flow energy saving strategy on a deep-mine cooling system*, Du Plessis G.E., Liebenberg L., Mathews E.H., Applied Energy, 102, 700-709, Copyright (2013), with permission from Elsevier)

Figure 79 shows a saving of at least 150 kW during periods when the evaporator water pumps operated at full load, typically during times when the chilled water demand was high. This is attributed to the base energy saving achieved by opening all control valves, previously used for flow control, and decreasing pump speeds in order to supply the design flow. This result proves the inefficiency of this standard flow control method used on large cooling systems and emphasises the potential which lies in improving these systems.

Figure 79 also indicates 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. Part-load pump savings of about 100 kW are observed for periods of low water demand. There is also a corresponding reduction in the daily volume of water (and hence cooling load), which must be chilled daily in order to meet the demand.

It can be summarised that the implemented evaporator water flow control method resulted in evaporator pumping energy savings of 69%. These savings were more or less equally divided between full-load savings realised by opening throttling valves and part-load savings realised by varying the flow in proportion to the chilled water demand.

8.2.2 Condenser pumps

The condenser pump electrical energy savings realised by implementing the proposed condenser water flow control strategy are quantified in Figures 80 to 82. As with the evaporator pumps, the water flow rates and electrical power input values were considered for the condenser pump group as a whole.

Figure 80 shows the daily average condenser pump input power and condenser flow rate before and after implementation of the strategy.

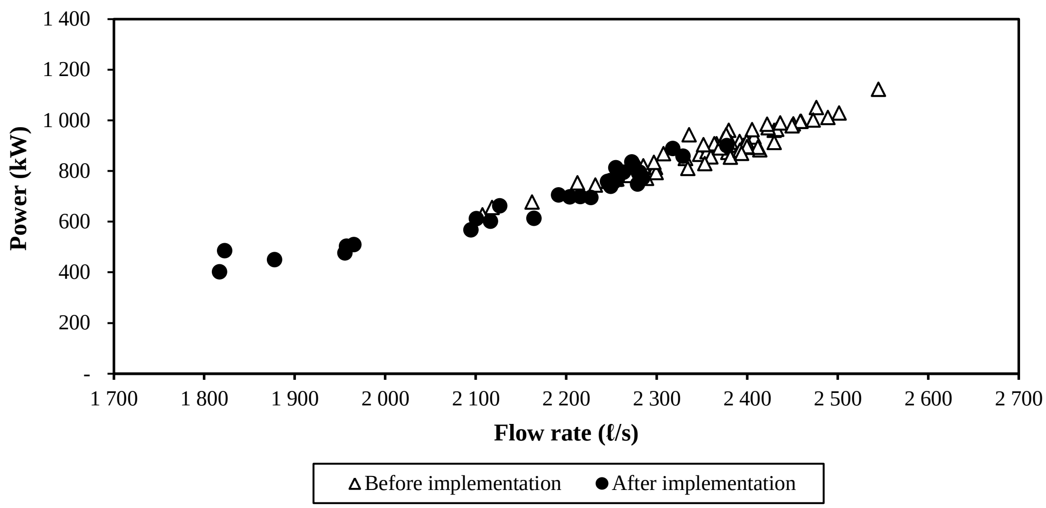

Figure 80 Daily average condenser pump power as a function of total condenser water flow rate (Kusasalethu)

Figure 80 indicates that the average decrease in daily water flow was 8%, while average pumping power decreased by 21%. This is less than the percentage savings achieved by the evaporator pumps - firstly because VSDs were applied to a smaller portion of the condenser pump system (three of five condenser pumps as opposed to three of four evaporator pumps).

Secondly, the water flow in the condenser system was not as restrictive as in the evaporator system before implementation. Also, the condenser flow control according to temperature difference is significantly slower to react and modulate because of the delay time it takes for a temperature difference to change according to the heat load and flow rate in the heat exchanger .

However, as previously mentioned, these condenser pumps have large installed power capacities, and a power saving of 189 kW was still achieved. This forms 7.2% of the total savings and 2.6% of the pre-implementation total plant power consumption.

The average daily profiles of the condenser pump group before and after strategy implementation are shown in Figure 81. Similar to the evaporator average profile, the power trends are relatively constant due to the heat load constantly modulating at different parts of the various days in proportion to the evaporator cooling load.

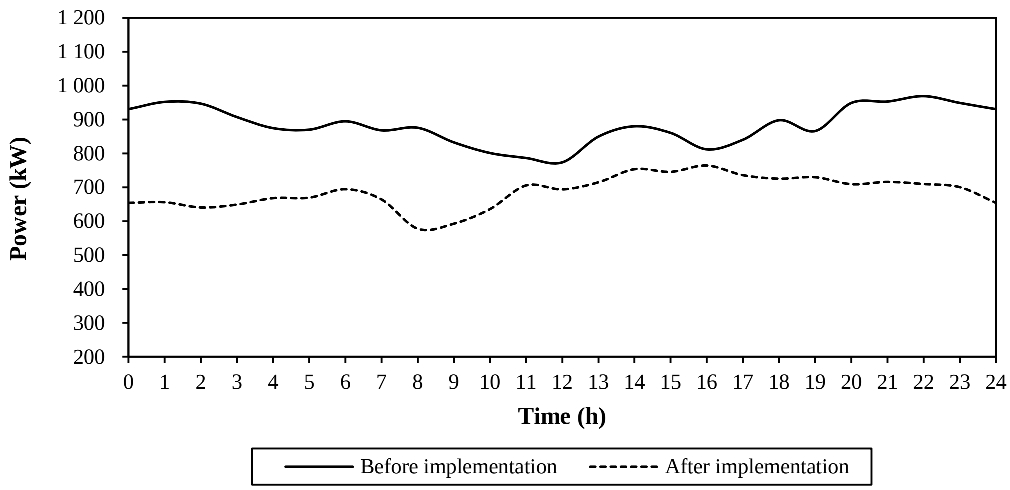

Figure 81 Average daily profile of condenser pump power (Kusasalethu)

Typical daily power profiles are shown in Figure 82. The same sample days were used as in Figure 79 for comparative purposes.

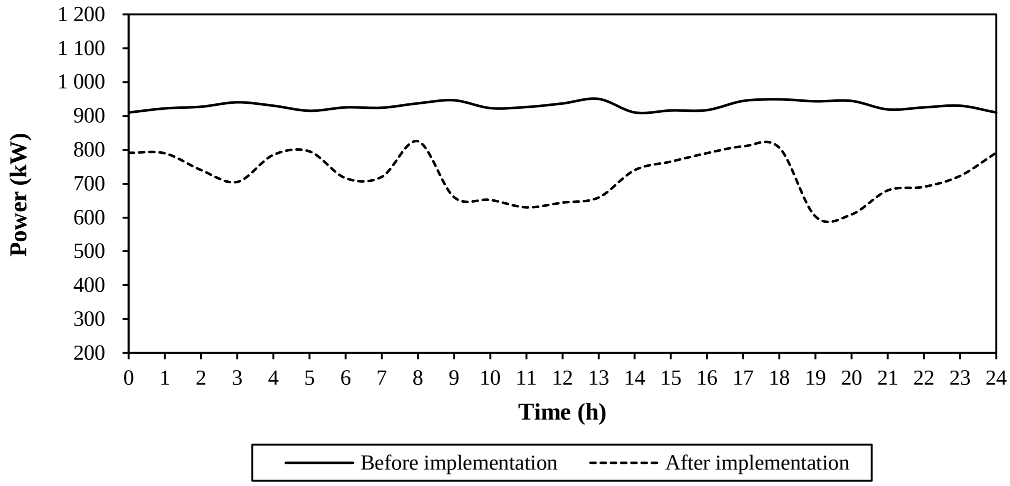

Figure 82 Typical daily profile of condenser pump power (Kusasalethu)

Figure 82 shows that the water control method of maintaining an average water temperature difference across the condensers was less sensitive to heat load changes than the evaporator flow was to dam level changes. This is due to the heat transfer time delay mentioned previously. However, the resemblance of the post-implementation profile to the evaporator profile in Figure 79 is apparent. This indicates that the control method enabled the condenser water flow to successfully adapt to the condenser heat load determined by the evaporator cooling load.

It was shown that the implemented condenser water flow control method resulted in condenser pumping energy savings of 21%. These savings resulted from full-load savings realised by opening throttling valves and part-load savings realised by varying the flow in proportion to the average thermal load of the condensers.

8.2.3 BAC pumps

The BAC return water pump savings realised by implementing the BAC supply and return water control are shown in Figures 83 to 85. Only the electrical power input of the return water pumps is considered here because the supply water is gravity fed and controlled by means of the newly installed control valves. The BAC system only has one water inlet and outlet (as shown in Figure 38).

This means that the daily effect of controlling the supply water will be reflected by the daily power consumption of the return pumps. The direct saving contribution of the pumps controlling the drainage dam level will also be reflected in their power consumption.

Figure 83 shows the daily average of the BAC return pump group power as a function of the daily average BAC water flow rate. Fewer data points are shown than, for example, in Figures 77 and 80. This is because only pre- and post-implementation days that corresponded very closely in ambient conditions and thermal loading (averages and profiles) could be considered.

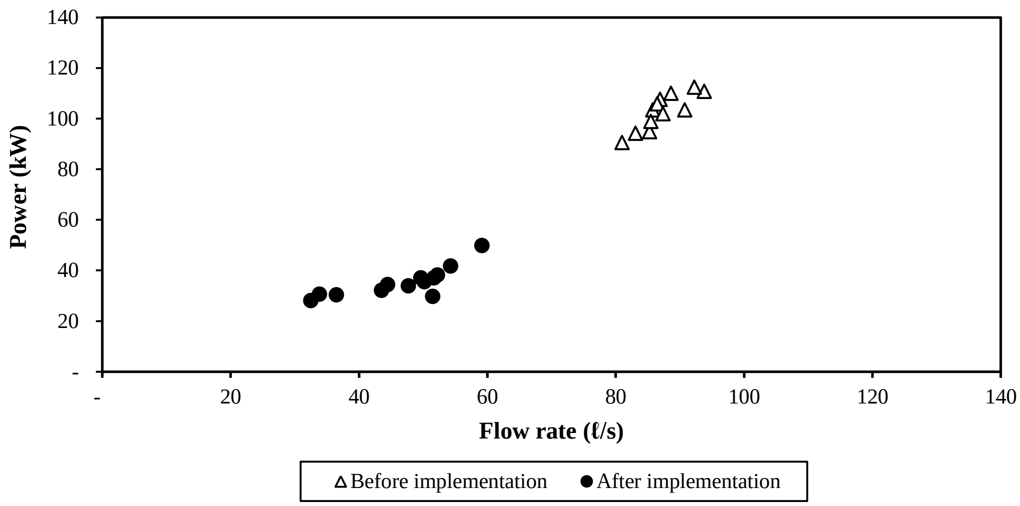

Figure 83 Daily average BAC pump power as a function of total BAC water flow rate (Kusasalethu)

It is apparent from Figure 83 that there was a significant decrease in the average daily flow rate of water through the BAC. The average reduction in flow rate was 46%. This is the result of the supply water valves controlling the flow rate in direct proportion to the ambient air enthalpy. There is no overlapping of pre- and post-implementation data points and all points are for comparable ambient conditions. This clearly shows the degree of overcooling that was supplied by the BAC before valve control implementation. However, these flow savings will be offset against the changes in cooling service delivery discussed in the following chapters.

The BAC return water pumping power decreased by an average of 66% as a result of the reduced daily water volume and the control according to the drainage dam level. Although this is a large percentage, the pumps are relatively small. Therefore, this saving only translates to 2.6% of the total energy savings and 0.9% of the pre-implementation total cooling system power consumption.

As indicated in Figure 83, the average daily pre-implementation power of the BAC return pumps was 104 kW. This is low considering that three 75 kW pumps are available. The reason for this is that the mine usually operated only two of the pumps at intermittent schedules. This demonstrates the importance of analysing the actual operational schedules of equipment before implementation and illustrates why two and not three VSDs were supplied.

The average daily power profiles of the BAC return pump group are shown in Figure 84.

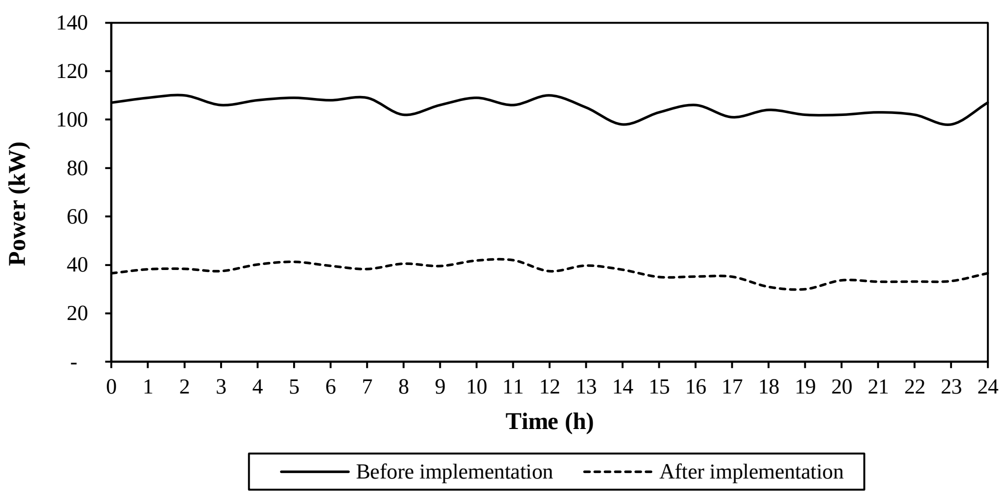

Figure 84 Average daily profile of BAC pump power (Kusasalethu)

Figure 84 shows the average reduction in return pumping power clearly. There was an average reduction of about 68 kW. However, the control and daily fluctuations are not reflected well. To investigate these, Figure 85 (Du Plessis et al. 2013a) shows the daily power profile for a typical sample day.

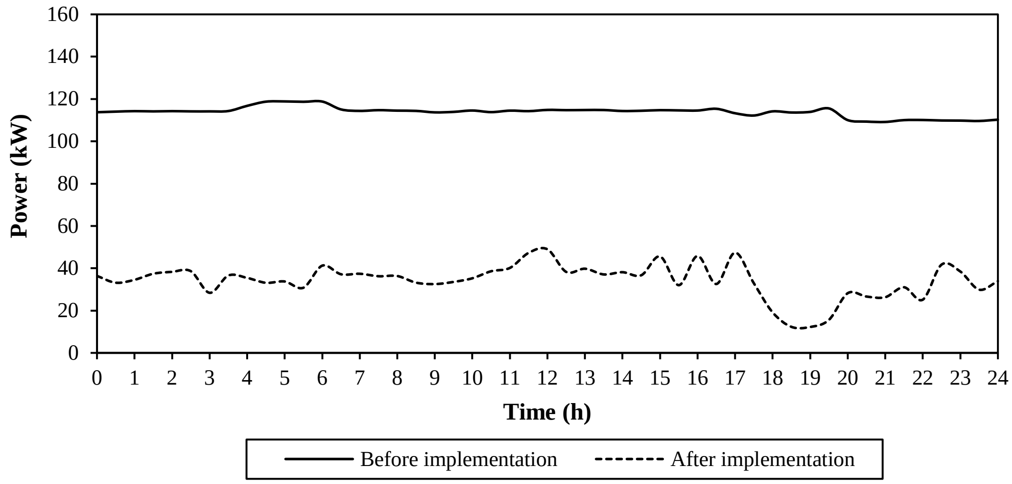

Figure 85 Typical daily profile of BAC pump power (Kusasalethu) (Reprinted from *Case study: The effects of a variable flow energy saving strategy on a deep-mine cooling system*, Du Plessis G.E., Liebenberg L., Mathews E.H., Applied Energy, 102, 700-709, Copyright (2013), with permission from Elsevier)

For the sample day considered in Figure 85, it can be seen that there was 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. This base BAC water flow decrease not only realises return water pump savings as discussed, but also significantly decreases the daily chilled water demand on the chillers.

Figure 85 also shows the fluctuation of BAC return water pumping power in order to maintain a specified BAC water drainage dam level. This realised further savings as shown by the power profile. However, the base and indirect savings realised by decreasing the chilled water demand is of greater significance.

In summary, it was shown that the BAC water flow control on both supply and return lines resulted in BAC return pump power savings of 66%. This was mainly the result of a significant water flow reduction by the supply control valves as made possible by the original operation of the BAC and its water supply, which exceeded cooling demands. The effect of this flow reduction on the integrated cooling system energy usage, as well as on the system performance, is discussed further in following chapters.

8.2.4 Combined cooling system

The integrated cooling system energy savings that were realised are shown by Figures 86 to 89. The power usage of the entire system was monitored at the combined power supply feeders to the plant. The energy savings discussed here thus include the savings from the evaporator, condenser and BAC water flow control as described separately. These savings also include the net effects of daily flow reduction and pre-cooling tower replacement on the integrated system.

Figure 86 (Du Plessis et al. 2013a) shows the typical daily power profile of the combined cooling system, as measured and calculated using Equations 39 and 40. The sample day considered is the same as discussed in the previous sections.

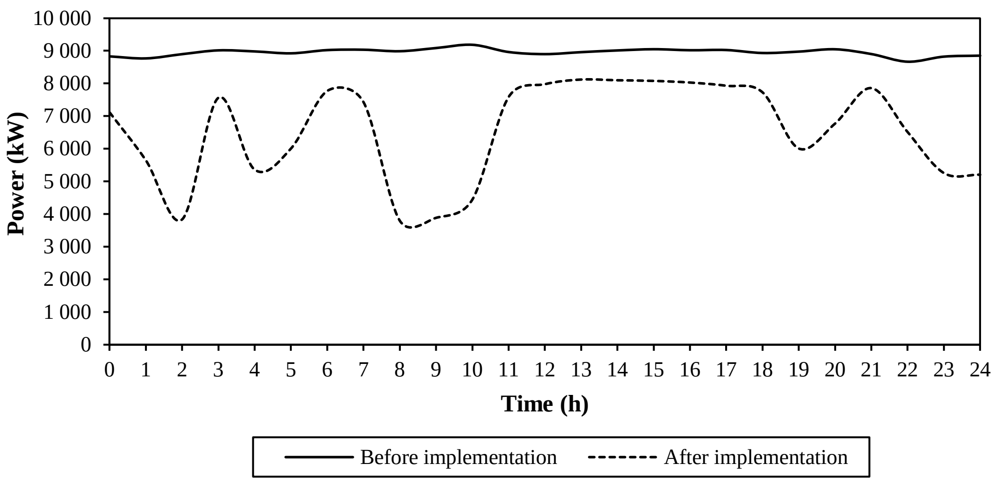

Figure 86 Typical daily profile of combined cooling system power input (Kusasalethu) (Reprinted from *Case study: The effects of a variable flow energy saving strategy on a deep-mine cooling system*, Du Plessis G.E., Liebenberg L., Mathews E.H., Applied Energy, 102, 700-709, Copyright (2013), with permission from Elsevier)

The average electrical energy saving for the sample day shown in Figure 86 was 2 394 kW, or 26.7% of the pre-implementation average. The post-implementation profile has two distinct attributes, namely part-load variation and a clear full-load offset.

The power fluctuation at part-load conditions is attributed primarily to the evaporator and condenser flow control strategies. This can be confirmed by noting the similarity between the post-implementation profiles of Figure 86, Figure 79 and, to a lesser extent, Figure 82.

The fluctuating effect of the BAC return pump control is not as noticeable because of the smaller pump capacities involved.

The distinct full-load offset of about 1 MW seen in Figure 86 is the net result of mainly three contributing factors. First, a significant base portion of the savings from the evaporator and condenser flow control strategies was realised from opening all the appropriate control valves previously used to throttle the water flows to design points.

Second, there was a large reduction in the total daily volume of water which needed to be chilled by the chillers. Although the underground demand of chilled water stayed constant (as will be discussed in the next section) the flow to the BAC was reduced significantly. In addition, chilled water was no longer recycled to the pre-cooling dam in order to achieve the correct chiller inlet water temperature. This further reduced the daily water volume handled by the chillers, decreasing the daily cooling load on the machines proportionally.

The third factor is the effect of the addition of the new pre-cooling towers. This is in fact a contribution to the second factor discussed already. 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 ºC. This means that the more efficient operation of the new pre-cooling towers enabled the direct supply of colder water to the evaporators. The new pre-cooling towers therefore allowed for the decrease in water flow supplied to the chillers and BAC without increasing the inlet temperature and hence the load on the chillers. The efficiency increase of the pre-cooling towers is discussed further in following sections.

The combined energy savings contributed to pre-cooling tower replacement and chilled water reductions amounted to an average of 29.9% of the combined plant electrical energy usage before implementation. This represents 83.5% of the total savings. The variable water flow strategies therefore 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.

The average daily power profile of the combined cooling system needs to be evaluated separately for summer and winter. This is because of the different operational requirements associated with the different seasons. Figure 87 and Figure 88 show the average summer and winter daily power profiles of the combined cooling system respectively. The post-implementation data considered was the first two months of performance assessment for summer, and the last month of performance assessment for winter.

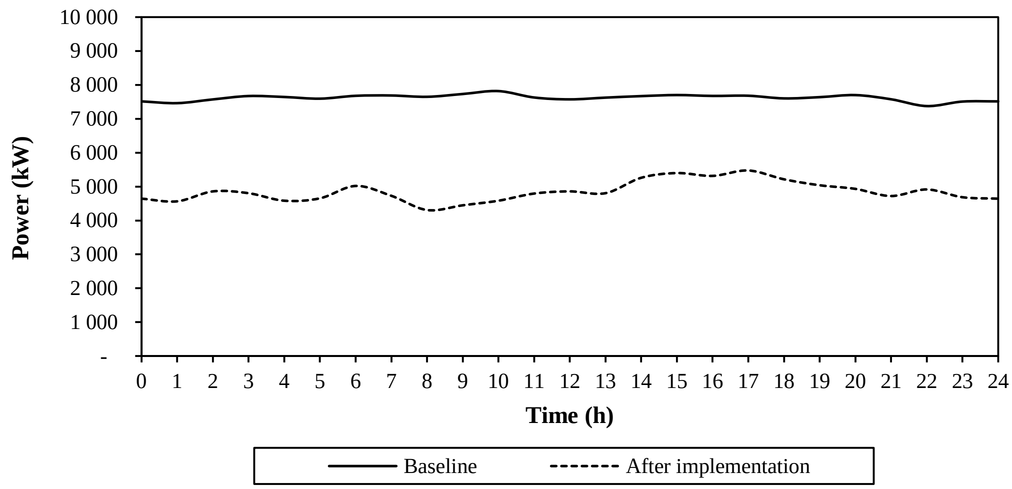

Figure 87 Average summer daily profile of combined cooling system power input (Kusasalethu)

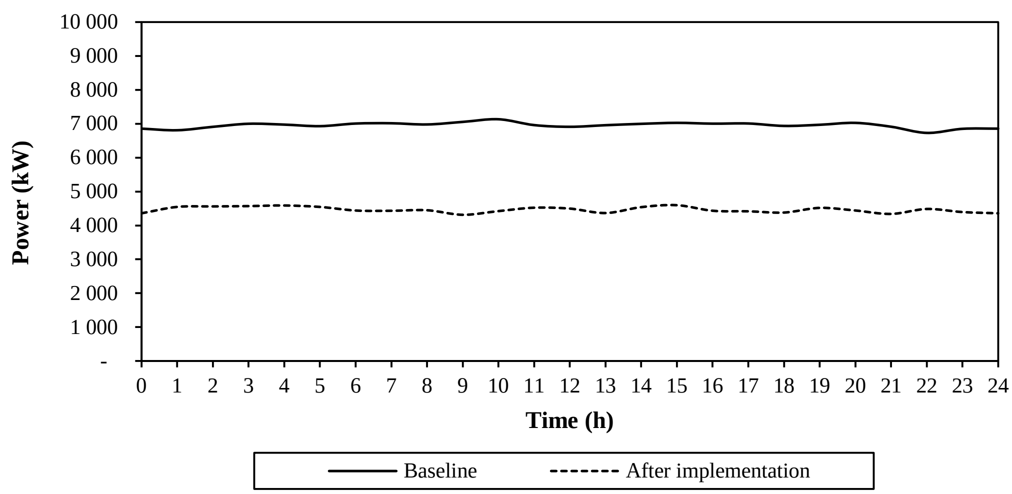

Figure 88 Average winter daily profile of combined cooling system power input (Kusasalethu)

Figure 87 shows that the average power consumption of the combined cooling system decreased by 2 591 kW or 34% during summer. Figure 88 shows that the average power consumption decreased by 2 483 kW or 36% during winter. The saving is seen to remain relatively constant, with a slight percentage increase in winter as a result of the lower associated pre-implementation baseline.

The tracked daily performance of the energy saving strategies for the three months under consideration is shown in Figure 89.

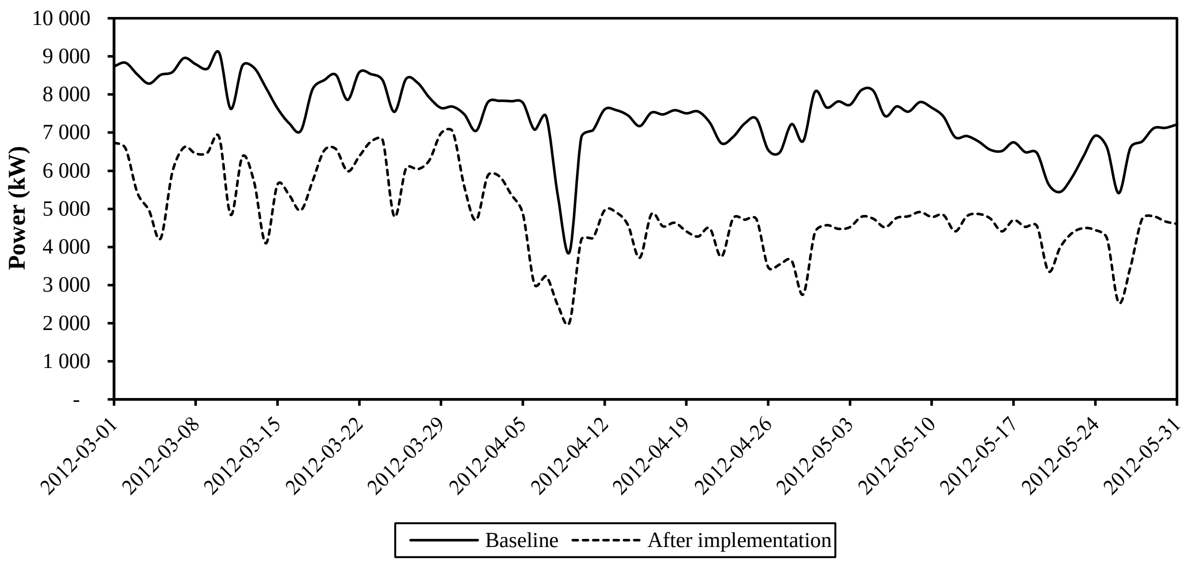

Figure 89 Daily average power input of combined cooling system (Kusasalethu)

Figure 89 indicates that the baseline and post-implementation daily average power consumption follow the same general trends. This is to be expected because the shown baseline values are scaled proportionally according to Equation 40 and the appropriate daily savings calculated from Equation 39.

The realised average daily saving in combined cooling plant power consumption for the entire period shown in Figure 89 was 2 609 kW, or 35.4% of the pre-implementation power consumption. This significant saving is reported with a high confidence level resulting from the approved measurement and verification procedures followed as described in Chapter 7.

8.2.5 *Summary*

A summary of the total energy savings measured and discussed, as well as those previously predicted by the simulation model, is given in Table 25.

Table 25 Combined cooling system energy saving summary (Kusasalethu)

	Baseline power (kW)	Actual power (kW)	Power saving (kW)	Measured saving (% of baseline)	Simulated saving (% of baseline)
March 2012	8 003	5 725	2 521	32	28
April 2012	7 133	4 230	2 903	41	37
May 2012	6 948	4 465	2 483	36	39
Average	**7 361**	**4 752**	**2 609**	**35.4**	**34.7**

When comparing the simulated predictions of energy savings given in Chapter 6 it is apparent that the measured savings are more than those predicted. As previously discussed however, the cooling system power usage has increased significantly since the time period on which the simulation was based and verified. It is therefore more applicable to compare the *percentage* savings measured to those predicted. It is shown in Table 25 that these savings correlate well for each month, with the simulation predicting an average combined saving of only 1.1% less than the measured saving.

The predicted values of the developed simulation model cannot be validated further here, because of the system operational changes already noted. However, the model was only used as a tool to predict the overall effect which the proposed strategies would have on a given large cooling system and its accuracy was verified in Chapter 6. The observation that the relative predicted and measured savings agree so well only serves as an emphasis that the simulation is a viable means to investigate the validity of the strategies on a cooling system.

It can be concluded that the average electrical energy usage of the Kusasalethu surface cooling system was reduced by 35.4% by implementing the energy saving strategy proposed, described and simulated in this study. This saving includes reduced water pumping power at part- and full-load conditions, decreased chiller input power at part-load conditions and decreased water volumes handled by the chillers as a result of the new pre-cooling towers, no recycling of chilled water and reduced BAC water supply flow.

8.3 Service delivery

The energy savings realised by implementing the developed strategies cannot be evaluated without considering the effects on the service delivery of the integrated cooling system. Although the strategies were developed specifically with the mine service delivery as design requirements, it is important to measure and verify these effects after actual implementation.

Productivity and safety are main priorities on deep mines. It shown in Chapter 2, if the specified chilled water dam temperature and level as well as the shaft ventilation air wet-bulb temperature remain unchanged, there will be no adverse effect on the productivity and safety of the mine and its workers.

8.3.1 Chilled water

The effects of the energy saving strategies on the mine chilled water delivery parameters are shown in Figures 90 to 93. As before, only comparable data sets before and after implementation were considered.

Figure 90 (Du Plessis et al. 2013b) shows the daily average chilled water dam temperature and total volume of water sent underground before and after implementation.

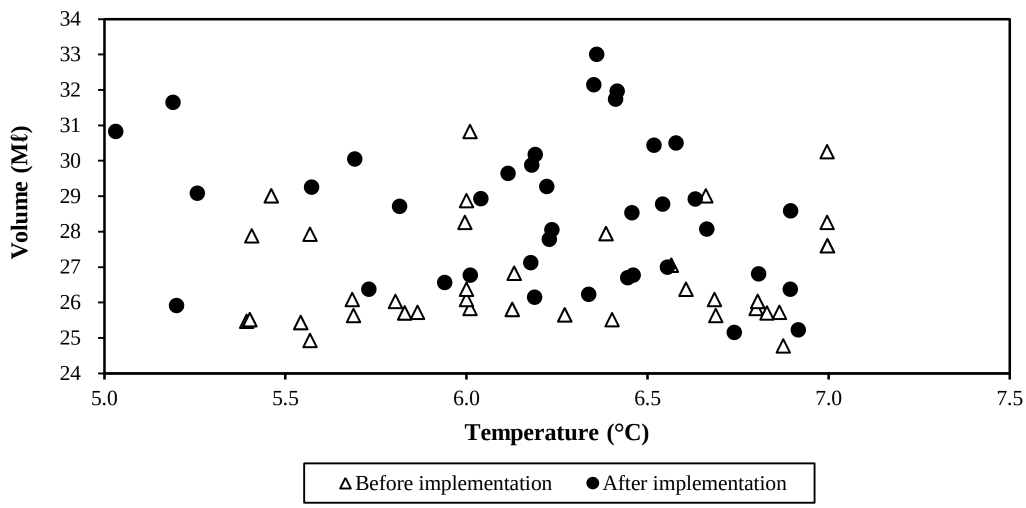

Figure 90 Daily average chilled water dam temperature and water volume sent underground (Kusasalethu) (Reprinted from *A versatile energy management system for large integrated cooling systems*, Du Plessis G.E., Liebenberg L., Mathews E.H., Du Plessis J.N., Energy Conversion and Management, 66, 312-325, Copyright (2013), with permission from Elsevier)

It can be seen in Figure 90 that before implementation of the energy saving strategy the chilled water dam temperature varied between 5.3 ºC and 7 ºC with a design point of 6 ºC. Also, the typical volume of chilled water sent underground varied between 24.5 Mℓ and 30.5 Mℓ per day with a design point of 27 Mℓ per 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.

Figure 90 shows that the average chilled water dam temperature after implementation of the energy saving strategy remained below the upper limit, averaging at 6.4 ºC. This is only a marginal increase in service water temperature resulting from the decreased evaporator flow and decreased BAC water usage.

It is apparent that the compressor guide vane 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 stay in the dam for longer periods than previously, leading to a temperature rise. However, it was found that the chilled water below 7 ºC is acceptable to the mine and this is therefore not seen as problematic.

Figure 90 also indicates that the daily volume of water sent underground was 27.4 Mℓ, remaining well above the lower limit of 24.5 Mℓ. This indicates that there was no reduction in service water supply and availability as a result of the reduced evaporator and BAC flow rates.

Although it was shown that the average daily values of the chilled water service delivery requirements were not compromised, it is also important to evaluate typical daily operation profiles to ensure that the parameters do not vary and fluctuate unacceptably. Figure 91 shows the typical daily profile of the chilled water dam temperature for days with similar underground water consumption and thermal loading before and after implementation.

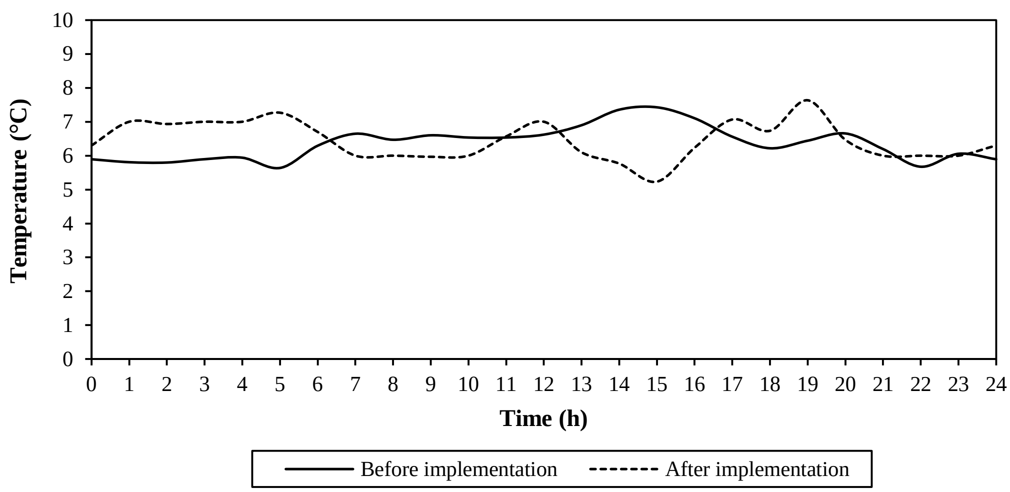

Figure 91 Typical daily profile of chilled water dam temperature (Kusasalethu)

The average temperature for the sample day considered in Figure 91 was 6.4 ºC before implementation and 6.5 ºC after implementation, confirming the small difference in average values discussed already. The profiles are also seen to be similar in terms of deviation from the respective mean temperatures, always remaining between 5 ºC and 7 ºC.

The main difference between the profiles relates to the time periods and duration of the temperature fluctuations. These trends depend on the chilled water dam inlet temperature, inlet water flow rate and various outlet water flow rates. The inlet temperature remained relatively constant as a result of the refrigerant compressor guide vane control, as already mentioned. The inlet flow rate changed from a constantly high flow to varying lower flows. The same can be said for the outflow to the BAC and back-pass line. These variations were not constant because the demand for water underground was not constant and therefore a different profile would be observed for every day. However, the Kusasalethu mine accepts variations between 5 ºC and 7 ºC. The typical daily profile of the chilled water temperature therefore stayed within acceptable limits.

The fluctuation in the chilled water dam level was considered to investigate the control of chilled water availability. Figure 92 shows the typical daily profile of the chilled water dam level before and after implementation.

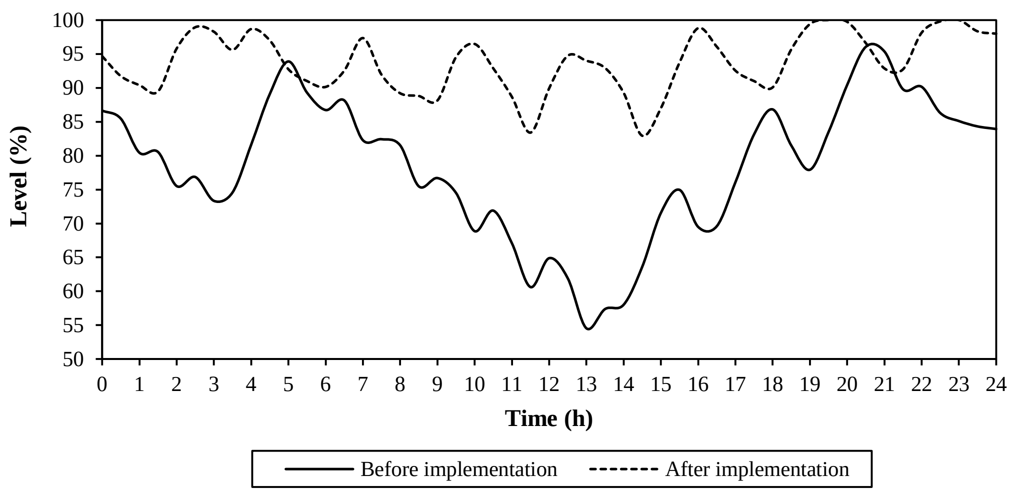

Figure 92 Typical daily profile of chilled water dam level (Kusasalethu)

It can be seen in Figure 92 that the average daily dam levels improved significantly after implementation. For these typical days the average pre-implementation level was 78% and the post-implementation level was 94%. Considering that the set point level of the evaporator flow control strategy was 95%, the improvement is clear.

The variation in dam level throughout the day also decreased significantly as expected. 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.

The flow rate profile of chilled water sent underground during a typical 24-hour schedule is shown in Figure 93.

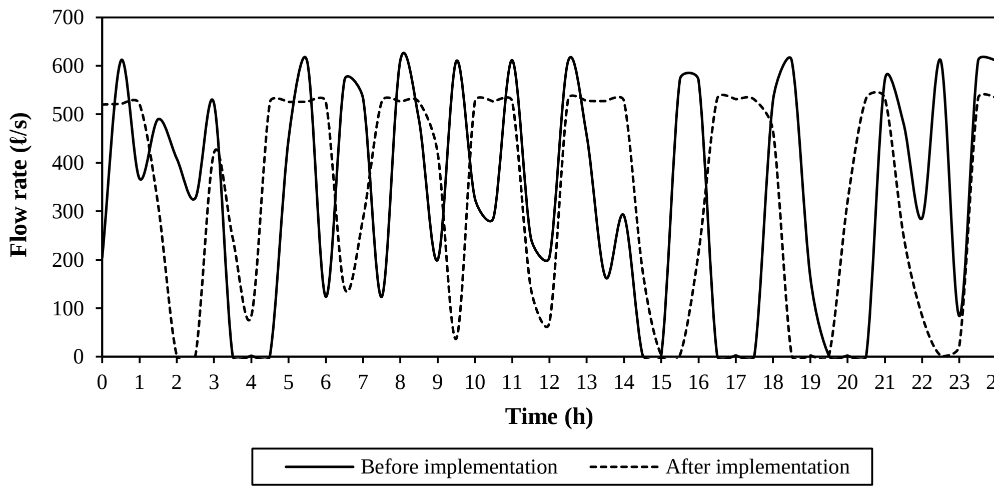

Figure 93 Typical daily profile of chilled water flow rate sent underground (Kusasalethu)

It can be seen in Figure 93 that the chilled water demand underground is not coupled to set schedules and that the flow rates change radically and intermittently as required. The main reason for this is that there are various underground water storage dams that each supply service water to different areas. The outflows of these dams are not scheduled and not well controlled. The result is often a sudden drop in one of the underground dam levels after water has been drawn there, subsequently requiring chilled water from the surface cooling system.

In Figure 93 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 longterm 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 (McPherson 1993). Both of these improvements result from the chilled water dam level being synchronised with the underground demand.

It was found that the implementation of the energy saving strategies did not adversely affect the availability and temperature of chilled water supplied to the mine. Daily average water temperatures and volumes as well as daily profiles of chilled water dam temperatures, levels and flow rates to underground were all maintained within the accepted limits or approved upon.

8.3.2 Ventilation air

The effect of the strategies on the cooling of ventilation air sent underground is investigated in Figures 94 and 95. It would have been ideal to compare the pre- and post-implementation wet-bulb air temperatures at the surface BAC outlet to evaluate the change in ventilation air cooling. Unfortunately, the Kusasalethu mine does not have any temperature or humidity sensors installed there due to maintenance constraints discussed before. Therefore, no sufficient historic data was available to use as a baseline.

The only location where the conditions of ventilation air had been monitored historically was at the inlet of an underground BAC at Level 75. This location enables the ventilation air conditions to be monitored directly at the entrance of the first main production area. It is in these working areas where the wet-bulb temperature must be kept below 27.5 ºC as discussed in Chapter 2. It was reported by the mine officials that the BAC inlet dry-bulb temperature and relative humidity (RH) before implementation allowed for sufficient cooling such that the outlet wet-bulb temperature complied with mine ventilation requirements for the production areas. Therefore, the only option to investigate the effects on ventilation air was to evaluate the changes in these measurements upon implementation of the energy saving strategy.

Figure 94 shows the daily average dry-bulb temperature and 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 in the production areas.

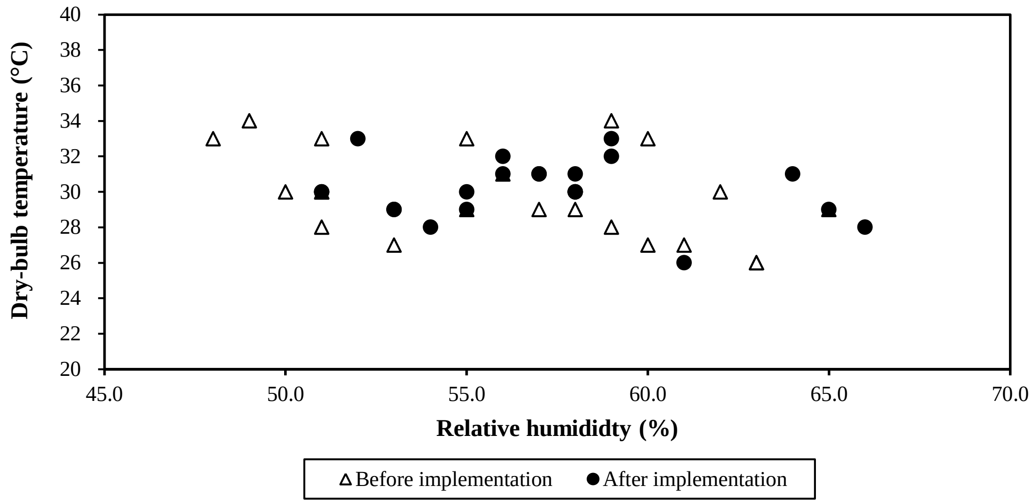

Figure 94 Daily average dry-bulb temperature and relative humidity at Level 75 BAC inlet (Kusasalethu)

Figure 94 shows that there were no major changes in pre- and post-implementation data points. Increases of 1.5% in the average dry-bulb temperature and 1.1% in the average RH were observed after strategy implementation. The reduction in BAC flow rate therefore did not significantly influence the effective cooling possible for the specific BAC design on Kusasalethu. This result suggests that the resultant cooling of ventilation air did not rely largely on the original high BAC flow rates. To investigate this further, the cooling efficiency of the BAC was evaluated as reported in the next section.

Figure 95 (Du Plessis et al. 2013a) shows typical daily profiles of the same parameters evaluated in Figure 94.

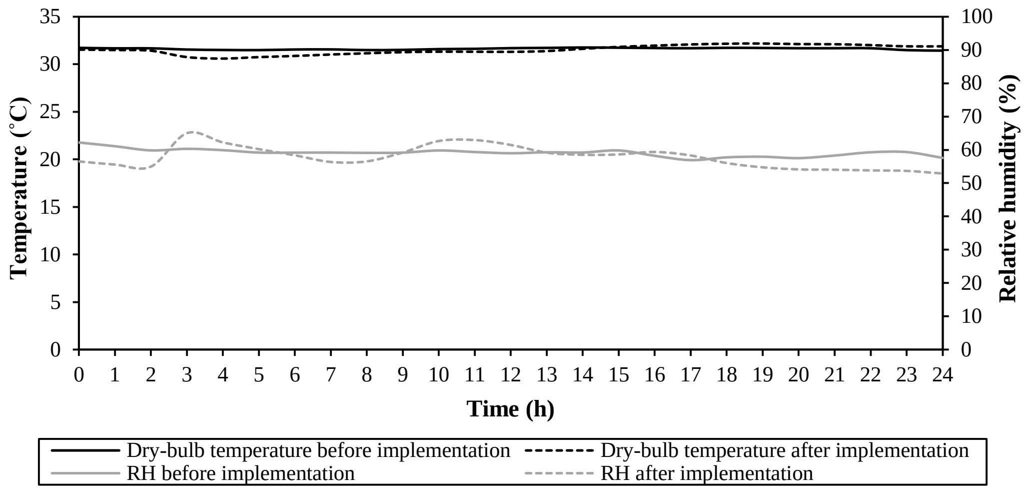

Figure 95 Typical daily profile of dry-bulb temperature and relative humidity at Level 75 BAC inlet (Kusasalethu)

(Reprinted from *Case study: The effects of a variable flow energy saving strategy on a deep-mine cooling system*, Du Plessis G.E., Liebenberg L., Mathews E.H., Applied Energy, 102, 700-709, Copyright (2013), with permission from Elsevier)

It can be seen in Figure 95 that the effect on daily temperature and RH profiles, after implementing surface BAC flow control, is negligible with an average difference of 2% in RH and 0.5% in dry-bulb temperature. The shapes of the pre- and post-implementation profiles also do not differ greatly, staying relatively constant in both cases. This emphasises the suggestion that the original BAC water flow rates were significantly over-specified.

As far as the only practically possible comparative evaluation is concerned, the ventilation air conditions at the Level 75 BAC inlet remained acceptably constant after implementation of the energy saving strategies on the surface cooling system. Assuming that the underground BAC efficiency remained unchanged, it follows that the wet-bulb requirements of the mine ventilation air were met because of the negligible change in underground BAC inlet conditions.

8.3.3 Summary

Table 26 provides a summary of the results regarding the effects of the implemented energy saving strategy on the key service delivery requirements of the combined cooling system.

Table 26 Summary of the effects on cooling system service delivery (Kusasalethu)

	Before implementation	After implementation	Change (%)
Chilled water dam temperature (ºC)	6.0	6.4	6.7
Chilled water daily demand (Mℓ/day)	27.0	27.4	1.5
Chilled water dam level (%)	78	94	20.5
RH of ventilation air at Level 75 (%)	56.2	57.1	1.5
Dry-bulb temperature of ventilation air at Level 75 (ºC)	29.8	30.1	1.1

Table 26 shows that the chilled water temperature and required flow underground remained relatively unchanged, while its availability improved significantly as a result of the chilled water dam level control strategy. The underground ventilation air conditions also remained relatively unchanged as far as this evaluation could determine. It can be concluded that the important service delivery requirements of the Kusasalethu surface cooling system were maintained within acceptable limits. It was thus shown that the implementation of the proposed and simulated energy saving strategy did not adversely affect any service delivery parameters.

8.4 System performance

It was found that the implementation of the developed energy saving strategies successfully realised significant savings and that there were no adverse effects on the service delivery of the cooling system. The last evaluation that is important to analyse in order to investigate the success of the energy saving strategy is the impact on the performance of the system and subsystems. It would be futile if energy savings are realised and service delivery maintained, but the efficient performance and operation of the system is degraded.

To evaluate the effects that the energy saving strategies had on the system performance of the Kusasalethu surface cooling system, various performance parameters can be considered, as discussed in Chapter 2. These include the performance of the newly implemented control system, the COPs and operation of the chillers, the efficiencies of pre-cooling towers, condenser cooling towers and BACs, the efficient performance of the electrical power supply system and the COP of the combined cooling system.

8.4.1 Control strategies

The control strategies developed to integrate and implement the energy saving measures were described in Chapters 4 and 6.2. If the actual performance of these strategies is not as originally intended, the proposed operation and savings might be compromised. Therefore, the performance and operation of the described strategies were validated by evaluation.

Only daily profiles of typical operation can be considered here because the strategies are executed in real-time. Figure 96 shows the typical daily profile of the evaporator flow control system. This includes the set point chilled water dam level, the actual measured dam level and the profile of the VSD group electrical AC output frequency.

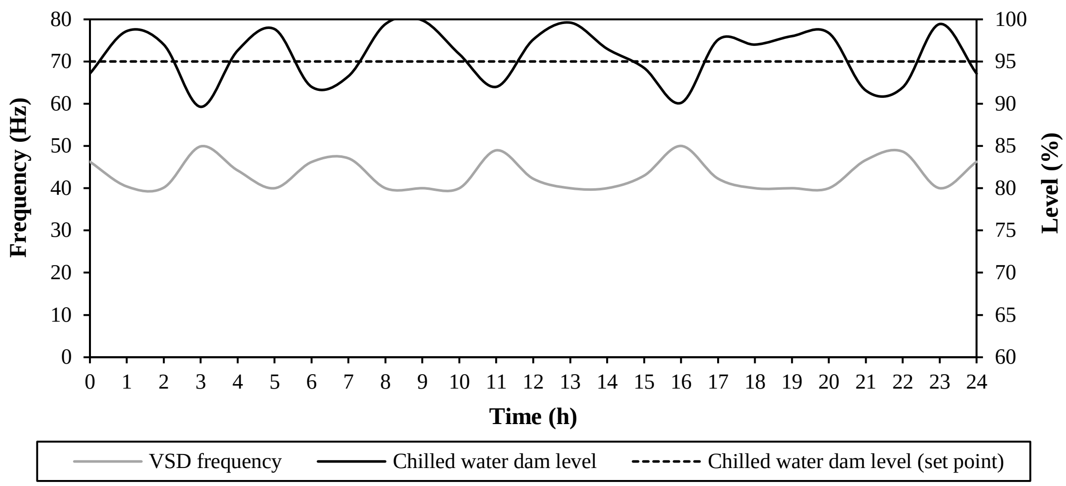

Figure 96 Typical daily profile of evaporator pump VSD frequency and chilled water dam level (Kusasalethu)

Figure 96 shows that the actual chilled water dam level fluctuated between 90% and 100%, with the set point level being 95%. The common frequency of the three evaporator pump VSDs fluctuated between the determined limits of 40 Hz and 50 Hz at an average of 43 Hz, as modulated in real-time by the PID control logic described in Chapter 7.

The profiles of the VSD frequency and the dam level are seen to be the inverse of each other. This is to be expected since a decrease in dam level (as a result of underground or BAC water demand) would lead to the VSDs modulating to increase the evaporator flow rate in order to maintain the dam level at the set point. The observation that the profiles are almost exactly mirrored suggests that the control strategy is sufficiently sensitive, because it responds quickly to dam level changes. This is confirmed by the evaporator pump power profiles as indicated in Figure 79.

It can be seen in Figure 96 that the times at which the pumps operated at 50 Hz were relatively short. This means that it was possible to operate the chillers at high loads for only short periods of the day and still maintain service delivery as reported in the previous section. This confirms the potential for the proposed strategies on large cooling systems such as these.

Figure 97 shows the typical daily profile of the condenser flow control system. This includes the set point average condenser water temperature rise, the actual temperature rise and the profile of the VSD group electrical AC output frequency.

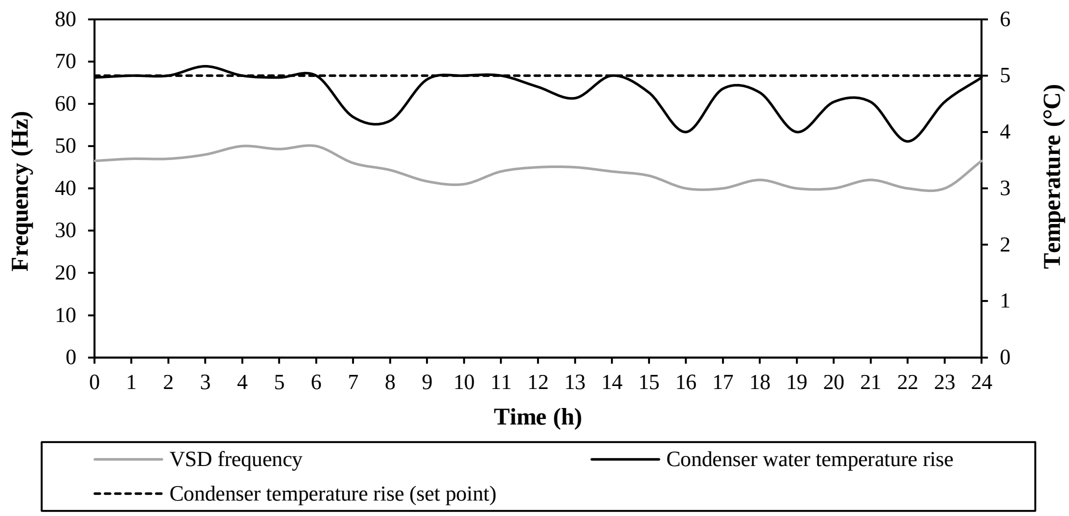

Figure 97 Typical daily profile of condenser pump VSD frequency and condenser water temperature rise (Kusasalethu)

Figure 97 shows that the average condenser water temperature rise fluctuated between 4 ºC and 5 ºC, with the set point being 5 ºC. The common frequency of the three condenser pump VSDs fluctuated between the determined limits of 40 Hz and 50 Hz at an average of 42 Hz, as calculated in real-time by the PID control logic.

In contrast to the evaporator flow control, the frequency profile of the condenser pump VSDs is seen to follow the same general shape as the water temperature rise across the condenser. The reason for this can be described by considering the water enthalpy rise as given by Equation 20. Suppose the outlet water temperature increases for a given inlet temperature as a result of a change in the heat load. For a constant water flow rate this would lead to an increase in the water temperature rise. The flow rate now compensates and increases proportionally in order to maintain the constant water temperature difference. The opposite happens for a decrease in the thermal loading of the condenser.

Figure 97 also shows that the condenser flow control was much less sensitive than the evaporator flow control. This is mainly attributed to the water outlet temperature taking more time to settle after changes to the flow rate and vice versa. This is confirmed by considering the delayed power profile of the condenser pumps in Figure 82 and the condenser PID logic in Chapter 7.

Generally, it can be seen that the condenser flow control system modulated its water flow according to temperature changes in turn caused by the changing chiller load. This was done while maintaining the water temperature rise to within 1 ºC of the set point and is therefore considered acceptable from a general control system performance evaluation point of view.

Figure 98 shows the typical daily profile of the ambient enthalpy and the corresponding common position of the BAC supply valve and supply water flow rate.

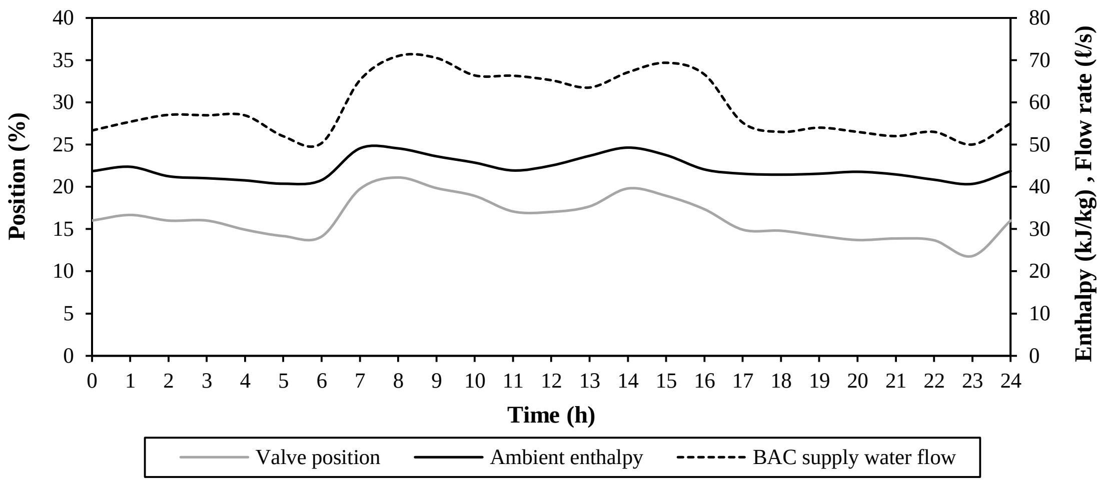

Figure 98 Typical daily profile of BAC supply water control valve position, ambient air enthalpy and BAC supply water flow rate (Kusasalethu)

Figure 98 shows that the ambient enthalpy for this sample day fluctuated between 40 kJ/kg and 50 kJ/kg. The BAC supply water valves opened correspondingly, varying between 12% and 22% at an average position of 16.3% open. As expected from the proposed control philosophy, the valve position is seen to follow the same profile as the ambient enthalpy. This shows that the forward-loop control strategy is sensitive to air temperature or RH changes reflected by the enthalpy.

The total supply water flow profile shown in Figure 98 indicates a significant average reduction of about 90 ℓ/s from the original flows, as discussed previously. This is attributed to the valve position being reduced by an average of 83.7% as shown in the figure. Given that underground ventilation air service delivery was maintained as evaluated, this emphasises the degree of redundant water flow that was utilised by the BAC previously.

It can be seen that the BAC supply water control strategy performed suitably by reducing a large percentage of the average flow and by controlling the water flow accurately according to the ambient conditions. This allowed the effective heat transfer to be functionally synchronised with the available ambient conditions and still provide sufficient cooling.

Figure 99 shows the typical daily profile of the BAC return water pump VSD frequency and the BAC drainage dam level.

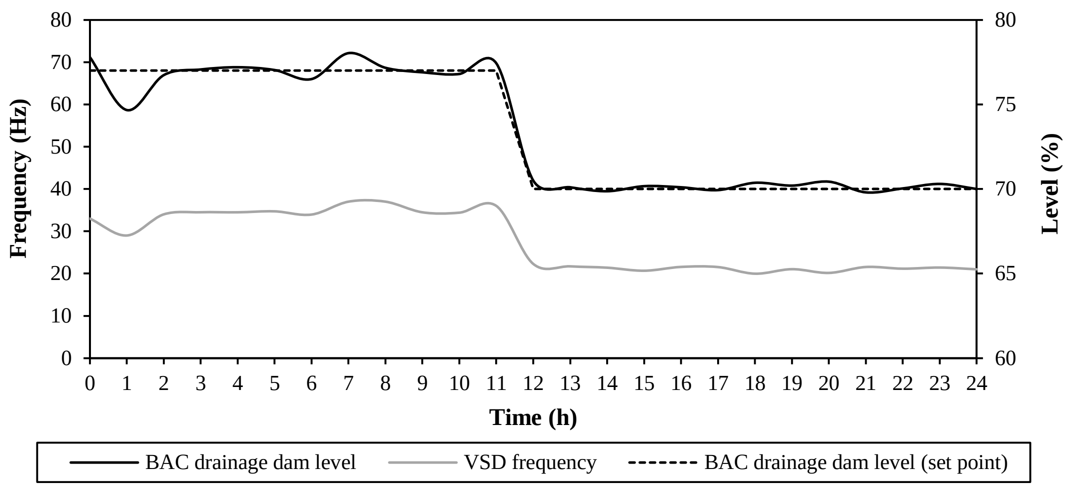

Figure 99 Typical daily profile of BAC return pump VSD frequency and BAC drainage dam level (Kusasalethu)

Figure 99 demonstrates that the VSD frequency profile followed the dam level fluctuations accurately. As expected this result is the opposite of the evaporator flow control because the pumps are draining water from a dam here, instead of supplying water to it. It can also be seen that the set point drainage dam level changed throughout the day. This was manually changed by the mine from 77% to 70% on the REMS-CA^{TM} platform and is included to show the control system response. It can be seen that the frequency of the VSDs responded appropriately.

The drainage dam level was controlled very accurately with an average standard deviation of only 0.26%. This is a good result, especially when comparing this profile to the chilled water dam level control shown in Figure 96. The reason for this pertains to the facts that the inlet and outlet flow rates of the BAC are significantly less in a control volume where both the inlet and outlet flows can be controlled by the implemented system.

The drainage dam water supply is therefore met by the demand as controlled by the pumps without significant delays, making accurate level control possible as shown.

It is concluded that the system performance of the control strategies implemented and controlled by the developed REMS-CA™ system was suitable and as proposed. The chilled water dam level, condenser heat load, BAC supply water flow and BAC return water flow were all controlled within the accepted limits and according to the functional specifications discussed earlier. It therefore follows that the performance of these control systems did not adversely affect any of the existing or newly installed equipment of the cooling system.

8.4.2 Chillers

The effects of the strategies on the performance of the chillers were evaluated next. As discussed in Chapter 2, this can be analysed by considering the COP of the machines before and after implementation. The daily failsafe tripped conditions of the chillers must also be evaluated.

When considering the chillers separately, the alterations that were brought about after implementation of the energy saving strategies involved the water flow rates of the evaporator and condenser being varied. To evaluate the separate contributions of these changes, controlled conditions were created by varying the two flows separately and simultaneously while the chillers were at full thermal load (100% guide vane position).

For simplicity, the COPs were not evaluated for each machine, but rather for the two parallel sets of machines in series. Only the COPs for the set containing chillers 3 and 4 are graphed, but the results of machines 1 and 2 are also given.

To calculate the COP values, Equations 1 to 3 were used. The evaporator water mass flow rate as well as inlet and outlet temperatures were measured to calculate the cooling load as given by Equation 2. The chiller work input could also be measured directly since the voltage, current and power factor values of each machine were measured by existing power meter panels. The accuracy and validity of the actual measured values and calculations are as discussed in Chapter 7.

The separate influences of variable water flow rates on chiller performance were evaluated by conducting a series of tests as mentioned already. During the first test, the condenser water flow was kept constant at design flow and the evaporator water flow control was applied while all machines initially operated at full load. The influence on the combined COP of chillers 3 and 4 is shown in Figure 100 (Du Plessis et al. 2013a).

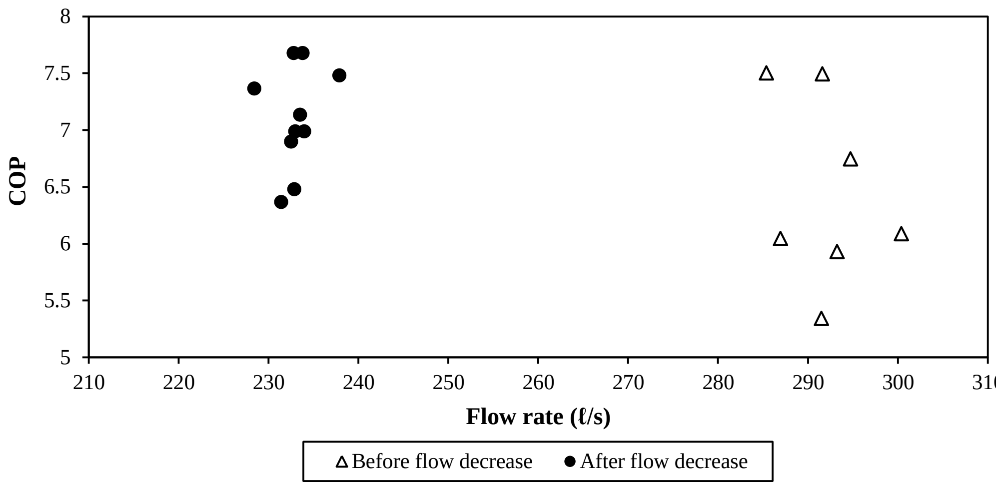

Figure 100 COP of chillers 3 and 4 with variable evaporator water flow (Kusasalethu) (Reprinted from *Case study: The effects of a variable flow energy saving strategy on a deep-mine cooling system*, Du Plessis G.E., Liebenberg L., Mathews E.H., Applied Energy, 102, 700-709, Copyright (2013), with permission from Elsevier)

It is shown in Figure 100 that the average COP of chillers 3 and 4 increased by 10%. Chillers 1 and 2 showed similar results, increasing by 11%. 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. As the cooling load is reduced (for a constant chilled water temperature difference), the compressor guide vanes close to modulate the refrigerant flow accordingly. 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 (Yu and Chan 2012).

Another test was conducted where the evaporator water flow rates were held at the design configuration while simply decreasing the condenser water flow. The influence on the combined COP of chillers 3 and 4 is shown in Figure 101 (Du Plessis et al. 2013a).

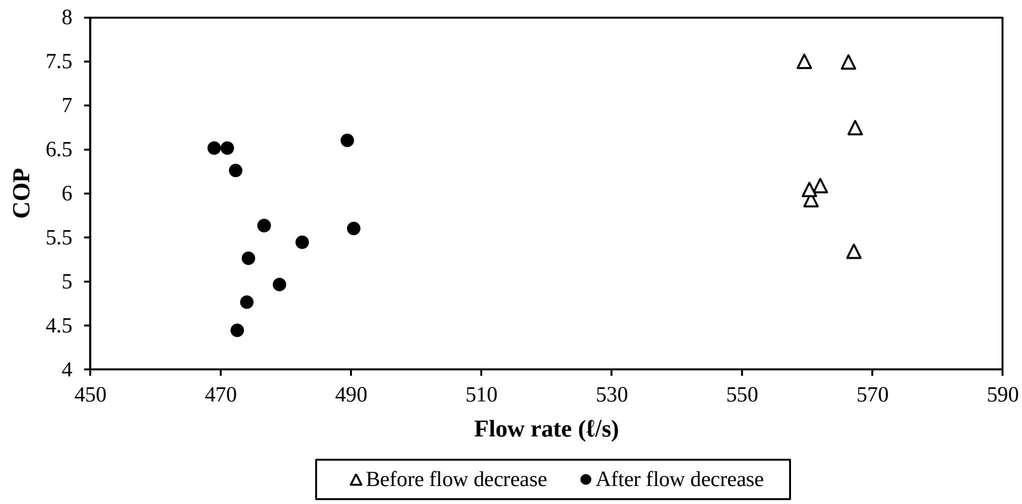

Figure 101 COP of chillers 3 and 4 with variable condenser water flow (Kusasalethu) (Reprinted from *Case study: The effects of a variable flow energy saving strategy on a deep-mine cooling system*, Du Plessis G.E., Liebenberg L., Mathews E.H., Applied Energy, 102, 700-709, Copyright (2013), with permission from Elsevier)

Figure 101 shows an average COP decrease of 12% for chillers 3 and 4. Chillers 1 and 2 showed similar results with the COP being reduced by 10%. This is mainly due to the increase in water temperature difference across the condenser for a constant cooling load, but at a lower water flow rate. The higher average water temperature increases the compressor refrigerant discharge pressure and hence the compression ratio required for the same cooling load which leads to a higher COP, as discussed in Chapter 4.

The net effect of simultaneous evaporator and condenser water flow control on the combined COP of chillers 3 and 4 is shown in Figure 102 (Du Plessis et al. 2013a).

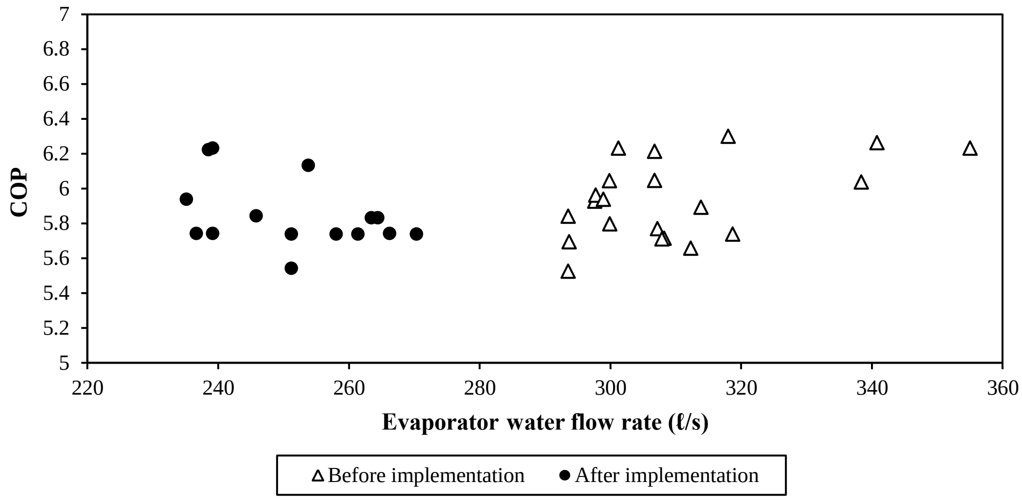

Figure 102 COP of chillers 3 and 4 with variable evaporator and condenser water flow (Kusasalethu) (Reprinted from *Case study: The effects of a variable flow energy saving strategy on a deep-mine cooling system*, Du Plessis G.E., Liebenberg L., Mathews E.H., Applied Energy, 102, 700-709, Copyright (2013), with permission from Elsevier)

Figure 102 shows that the COP of chillers 3 and 4 was maintained within 1.5% of the original value after implementation of both control strategies as proposed. Similarly, the COP of chillers 1 and 2 remained within 1.1% of the original values. Although water pump energy savings were realised in both the evaporator and condenser lines, the cooling efficiency of the chillers was not compromised. It is however important that both the evaporator and condenser water flow control strategies operate simultaneously.

The relatively few data points considered in Figures 100 to 102 is attributed to the limited available measurement intervals when the full-load testing was conducted as described. It was however sufficient to clearly show the trends and COP changes as discussed. The key results were that a reduced evaporator water flow tends to increase the COP, a reduced condenser flow tends to decrease the COP and a combination of the two essentially cancels out the individual effects and maintains a constant COP. This is provided that the flows are controlled within limits as described in this study.

As mentioned in Chapter 2, the chillers are designed to shut down, or “trip”, when specified set limits are exceeded. These limits relate to parameters such as water flow rates, water and refrigerant pressures, various temperatures, compressor vibration, compressor oil pressure and similar parameters.

A tripped condition therefore ensures that the efficient and safe operation of the machine is not compromised by a specific parameter change. It can therefore be used as a tool to further evaluate the effect of the implemented strategies on the performance of the machines. Figure 103 shows the number of daily tripped conditions logged for all four chillers together for comparable days and periods before, during and after control strategy implementation.

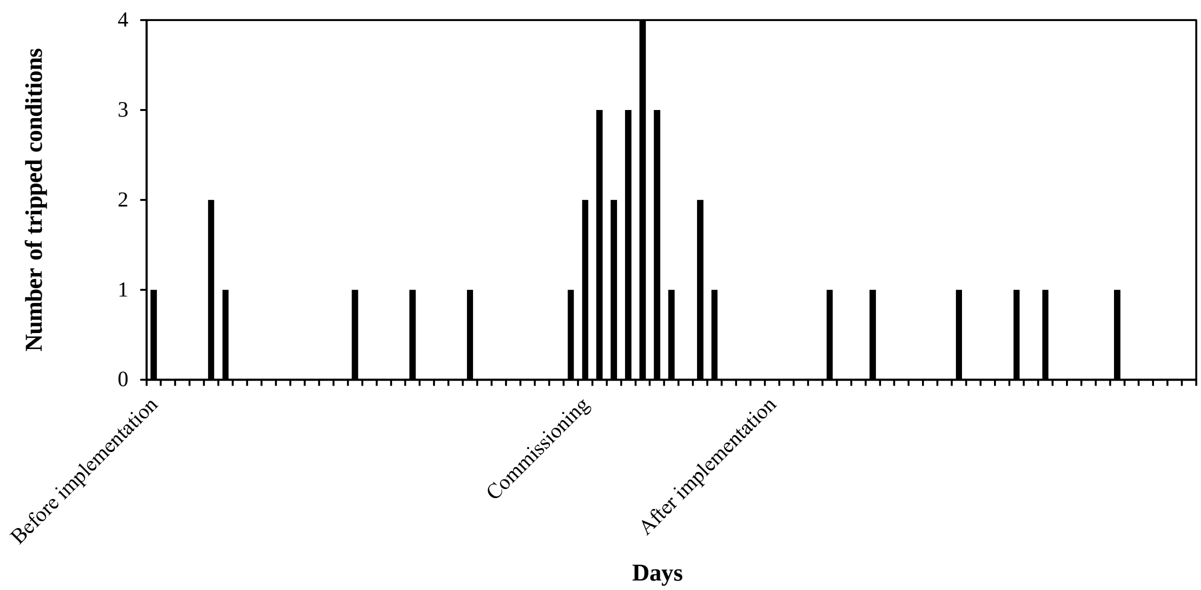

Figure 103 Number of daily chiller tripped conditions (Kusasalethu)

Figure 103 indicates that the total number of daily tripped conditions was eight before implementation, 20 during the commissioning phase and six after implementation. The high number during implementation is to be expected, because this is when parameters such as VSD frequency limits were determined experimentally. The important result here is that the total number of shutdowns during a comparable period after implementation was slightly less, although similar than before implementation. Although it is difficult to track the exact reasons why the plants tripped in each individual case, it is possible to make a relative comparison. This confirms the result that the general performance of the machines was not adversely affected by the implemented energy saving strategies.

It was shown that the performance of the chillers was not compromised as a result of the variable water flow strategies implemented at Kusasalethu. The COPs stayed relatively constant as a result of net effects of evaporator and condenser flow control as determined by a series of full-load tests. Furthermore, the number of daily tripped conditions that resulted from unacceptable operation parameters did not change significantly after implementation.

8.4.3 Pre-cooling towers

The effects of the variable-flow strategies on the three direct contact heat exchanger installations of the cooling system (the pre-cooling towers, the condenser cooling towers and the BAC) were investigated in similar ways. As described in Chapter 2.3, common ways to evaluate the performance of such heat exchangers are to consider the water-side and air-side efficiency of the system. Unfortunately, the air psychrometric conditions are not measured at the outlets of any of the three installations at Kusasalethu and thus no historic data is available. It was only possible to consider the water-side efficiency and effects from the available measuring points. This is however reasonable because the changes were made on the water-side of the heat exchangers and it is a comparative evaluation relative to the original performance.

The water-side efficiency of the cooling towers was calculated from Equation 6 by considering measured water temperature values before and after implementation. In addition, the cooling tower approach values were calculated from Equation 5 to evaluate the change in effective heat transfer more closely.

As discussed previously, the new pre-cooling towers were installed with the proposal that it will complement and increase the potential savings that can be realised by the different variable water flow strategies. This was also shown to be the simulated result in Chapter 6. The performance of the new pre-cooling towers was evaluated and compared to the performance of the old pre-cooling towers for comparable days. The viability of this evaluation is emphasised by the inlet water temperature, ambient conditions and supply water flow rate that all remained relatively unchanged before and after implementation.

The daily average approach values of the pre-cooling towers before and after the new cooling tower implementation are shown in Figure 104. As presented in Equation 5, the approach is the difference between the inlet ambient wet-bulb temperature and the outlet water temperature.

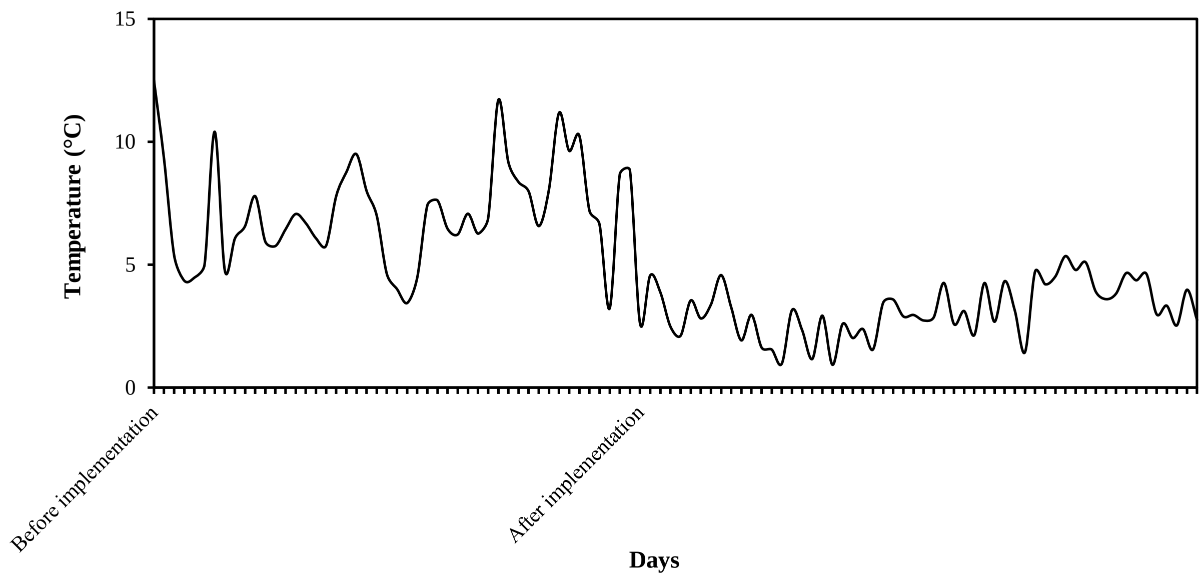

Figure 104 Daily average approach of pre-cooling towers (Kusasalethu)

Figure 104 shows that there was a significant reduction in the daily approach values after the new pre-cooling towers were installed. The average daily approach of 6.8 ºC decreased by 112% to an average of 3.2 ºC after implementation. This means that the new pre-cooling towers enable much more effective sensible and latent heat to be transferred from the water to the air. This is significant when taking into account that the inlet water temperature essentially stayed constant.

The daily average water-side efficiencies of the pre-cooling towers are shown in Figure 105.

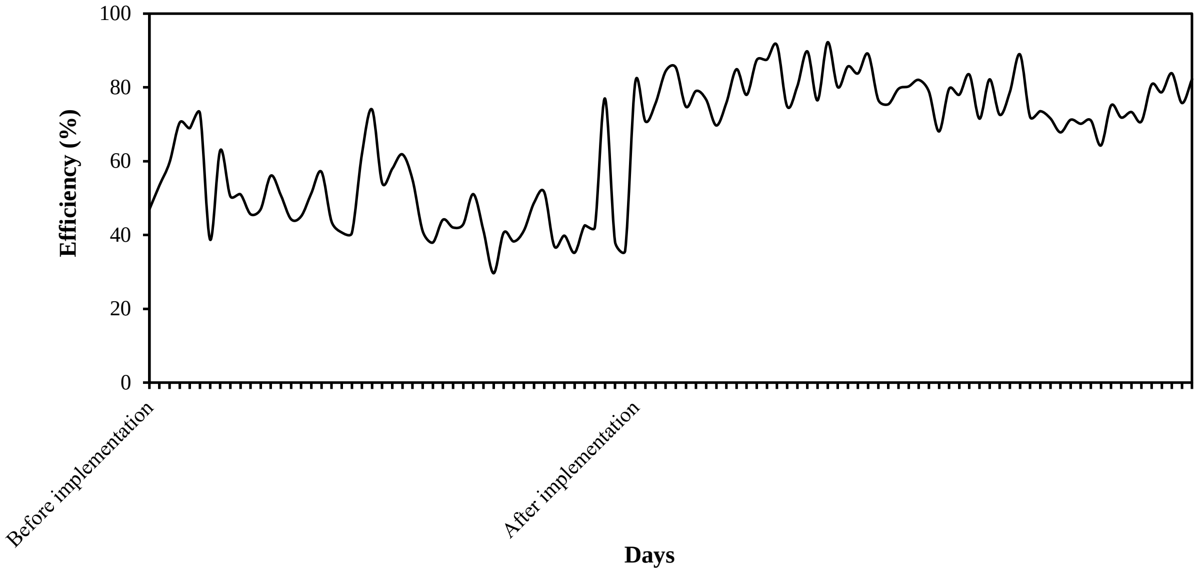

Figure 105 Daily average water-side efficiency of pre-cooling towers (Kusasalethu)

Figure 105 shows that the water-side cooling efficiency of the pre-cooling towers improved from an average of 50% to 78% after the new installation. This confirms the previous result of reduced approach values. Since air and water flow rates, water inlet temperature and average ambient conditions were all comparable, this improvement is largely attributed to the design and condition of the new towers. The new fill design and condition improved the area and duration of contact between the water and the air and thus improves the effectiveness of the heat transfer rate. The result also underlines the importance of maintaining equipment well, because the old pre-cooling towers were in a very bad state with some fill areas completely blocked or broken.

It is appropriate to also discuss the influence of the improved pre-cooling tower performance on the pre-cooling dam temperature. As already mentioned, the pre-cooling tower replacement was included in the energy saving strategy for Kusasalethu to enhance the performance of the variable-flow strategies. The average daily temperature of the pre-cooling dam and thus also of the evaporator inlet depends on various parameters. These include the water temperatures and flows from the pre-cooling tower, the BAC drainage dam and from the chilled water dam back-pass line as shown in Figure 38.

Figure 106 indicates the total water temperature drop from the pre-cooling tower inlet to the pre-cooling dam outlet before and after pre-cooling tower replacement. The temperature drops are subdivided according to the average relative contributions made by the various parameters that play roles in decreasing the water temperature of the pre-cooling dam. These contributions were calculated by considering the daily volumes and temperatures of the various inlets into the pre-cooling dam.

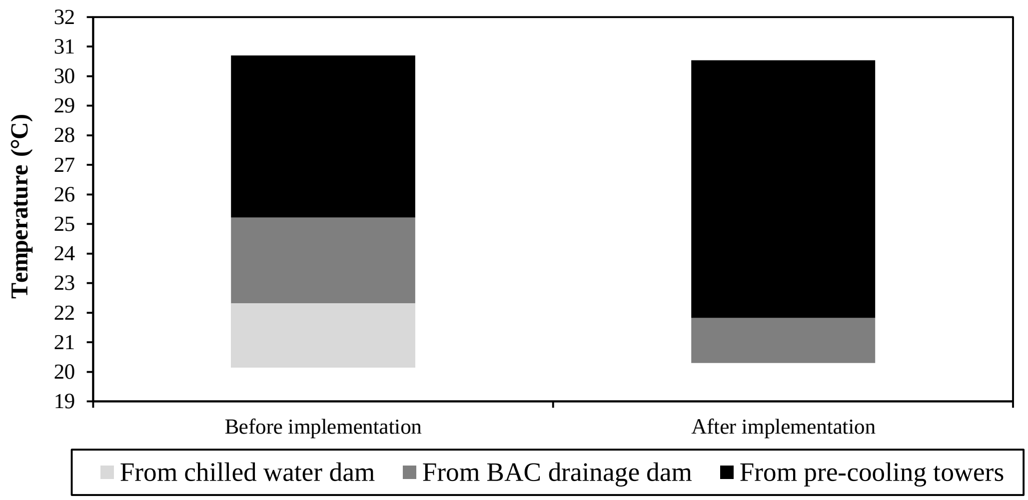

Figure 106 Relative contributions of average water temperature drop between pre-cooling tower inlet and pre-cooling dam outlet (Kusasalethu)

In Figure 106 it can be seen that the old pre-cooling towers realised only 52% of the total temperature drop and that significant volumes of colder water from the chilled dam and BAC drainage dam were added to lower the temperature sufficiently. The installation of the new towers subsequently increased the water temperature drop in the pre-cooling tower from 5.5 ºC to 8.7 ºC as a result of the improved cooling efficiency as discussed before. This enabled the back-pass water line from the chilled water dam to be shut off and the flow rate from the BAC drainage dam to be reduced, all without affecting the resultant average temperature in the pre-cooling dam. The contributions in the relative temperature drop in the dam changed to 85% from the more efficient towers, 15% from the BAC dam and 0% from the back-pass chilled water line as shown.

From the results in Figure 106 it is clear that the replacement of the pre-cooling towers complemented and enhanced the variable water flow strategies just as originally suggested in Chapter 6.2. The shut-off of the chilled water dam back-pass line enabled the chilled water dam to be controlled below 100% and the reduced BAC drainage dam requirements enabled the BAC supply flow reduction.

Figure 106 suggests that it would not have been possible to only replace the pre-cooling towers without considering the variable-flow strategies and still realise the reported savings. This is because the design evaporator flows were previously higher than the chilled water demand, leading to back-passing being a requirement. Similarly, the original operation of the BAC resulted in constantly high flow rates being returned to the pre-cooling dam. These necessary original operational methods would therefore have led to the pre-cooling dam temperature, decreasing to values below the evaporator inlet requirement if operated in conjunction with the new pre-cooling towers. This would typically lead to the chillers tripping because of low refrigerant pressures.

Conversely, the implemented variable-flow strategies would not have realised their full savings potential if the pre-cooling towers had not been replaced. This is because the lower BAC flow and chilled dam back-pass shut-off required for these strategies would have led to a significant increase in pre-cooling dam temperature. This in turn would lead to increased cooling loads and associated compressor requirements of the chillers.

It can be concluded that the implementation of the new pre-cooling towers resulted in a cooling tower water-side efficiency increase of 28%. This enabled the elimination of the back-passed chilled water and the reduction of the BAC water, while maintaining the average pre-cooling dam temperature as designed for the optimal operation of the refrigeration machines. Not only was the pre-cooling tower performance improved, but the variable-flow strategies were enhanced to enable large daily water and associated energy savings for this specific cooling system.

8.4.4 *Condenser cooling towers*

The effects of the strategy implementation on the performance of the condenser cooling towers were evaluated by the same parameters as for the pre-cooling towers. Figure 107 shows the daily average approach values before and after implementation as well as the total condenser water flow rate for days with comparable ambient conditions. The flow rate is included because it is the parameter that was varied by the developed condenser water flow control strategy.

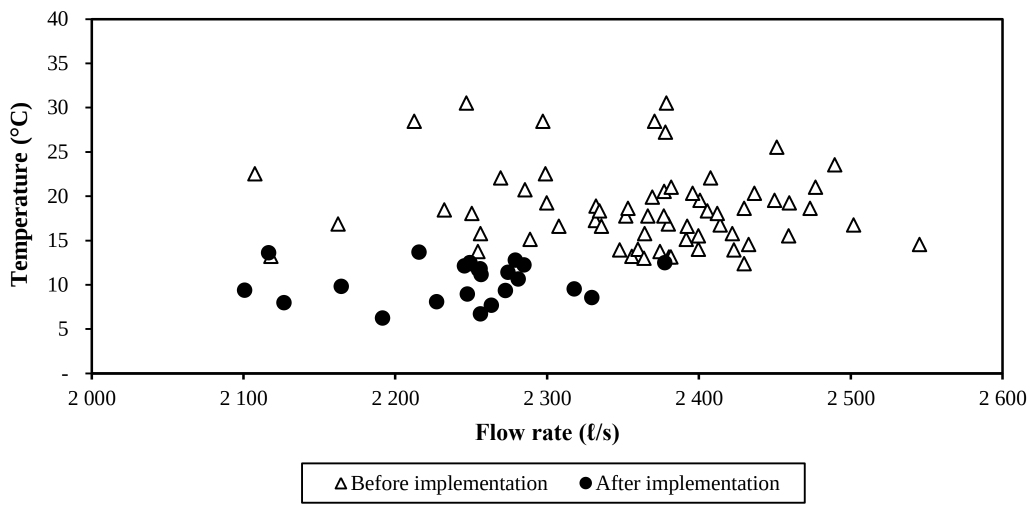

Figure 107 Daily average approach of condenser cooling towers as a function of total condenser water flow rate (Kusasalethu)

Figure 107 indicates a 38% reduction in the average approach of the condenser cooling tower after implementation of the condenser water flow control. The post-implementation data points are also more closely distributed than the pre-implementation measurements. These results should be considered in conjunction with the water-side efficiencies as shown in Figure 108.

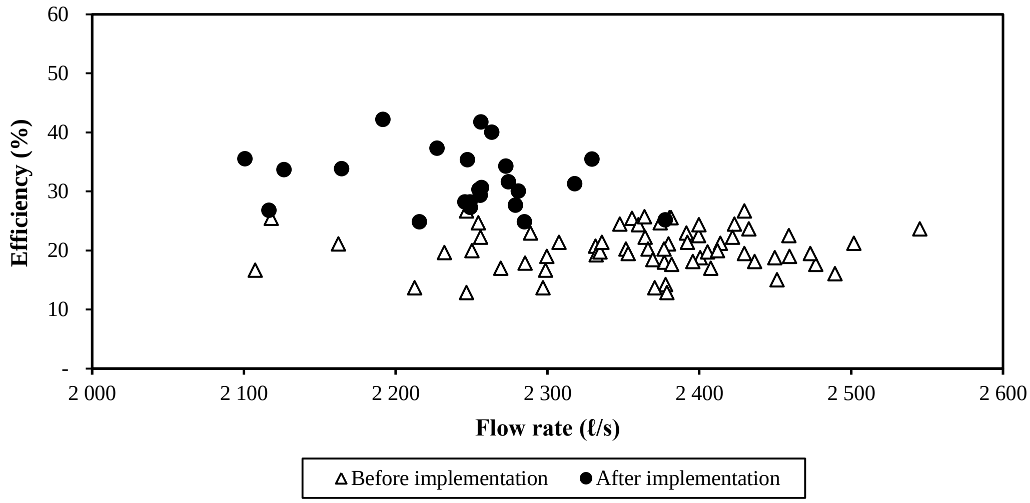

Figure 108 Daily average water-side efficiency of condenser cooling towers as a function of total condenser water flow rate (Kusasalethu)

Figure 108 shows that the water-side efficiency of the condenser cooling towers increased by 46% after implementation. Considering the reduced approach values shown in Figure 107 it can be seen that the performance of the condenser cooling tower generally improved.

It was observed that the range (given by Equation 4) remained reasonably constant before implementation. However, the absolute values of the condenser inlet and outlet water temperatures changed frequently according to ambient conditions and chiller cooling load for fixed water flow rates before implementation. This therefore led to great variance in approach and efficiency values of the condenser cooling tower as shown.

After implementation, the condenser water flow rate was modulated according to the heat load in order to maintain a set temperature rise of 5 ºC. This temperature rise corresponded to the design range usually obtained from the condenser cooling tower, depending on the ambient conditions. The approach values were subsequently improved and held more constant. This heat load modulation method also enabled the condenser inlet temperature to be held at a more steady state value for longer periods of time, improving the heat transfer efficiency of both condenser and cooling tower.

In essence, the set point of maintaining the original design temperature difference of 5 ºC (instead of a lower value) enabled the cooling tower to also perform closer to its originally designed higher efficiency.

It is noted from Figure 108 that the condenser cooling tower efficiencies were low, averaging at 20% before implementation and 29% after implementation. This is attributed to the poor condition that the cooling towers were seen to be in. As with the original pre-cooling towers, large portions of filling material are either blocked or broken down, leading to poor heat transfer rates. It is suggested to replace these towers to realise more efficient heat transfer that will translate into better modulation of the condenser water flow rate and hence better savings.

It was observed that the fixed-orifice nozzles maintained a relatively constant spray pattern, resulting in even fill wetting. This was because the lower flow limit of the control strategy was set to take this into account during commissioning. No excessive scaling or water 'spitting' was observed.

Based on the water-side measurements, it can be concluded that the performance of the condenser cooling towers was improved after implementation of the condenser water flow control strategy. The water-side efficiency increased by 46%. However, the efficiencies of the towers were not good in general and it was suggested that the energy efficiency of the condenser water circuit will be improved further by replacing the cooling towers.

8.4.5 Bulk air cooler

The effects of the variable-flow strategies on the performance of the BAC were evaluated by considering the same parameters as for the two sets of cooling towers. The calculation of these parameters differs slightly for an air cooler, because the heat is transferred from the air to the water instead of the other way around. The negative of the results obtained directly from Equations 4 to 6 were therefore used for BAC calculations.

Figure 109 shows the daily average approach values of the BAC and its supply water flow rates for comparable ambient conditions before and after implementation.

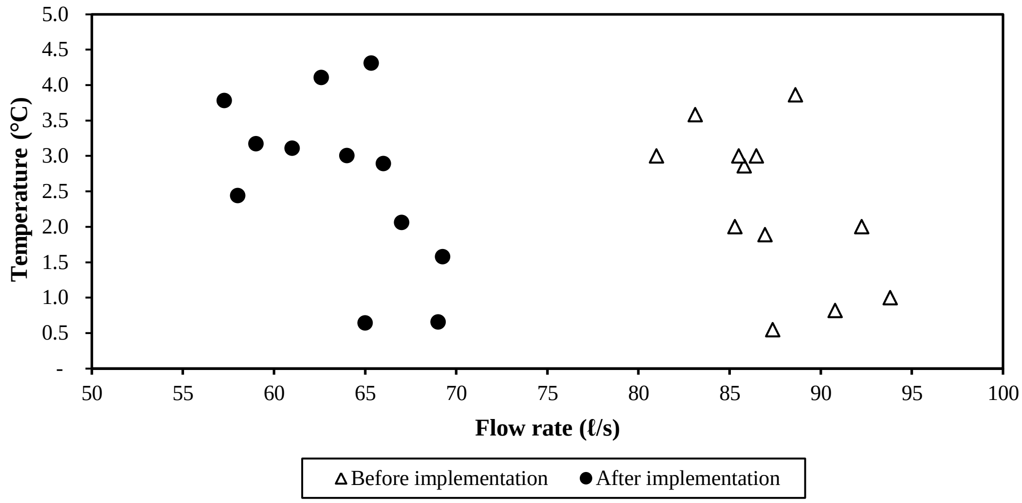

Figure 109 Daily average approach of BAC as a function of total BAC water flow rate (Kusasalethu)

It can be seen in Figure 109 that the average approach values stayed reasonably constant after the implementation of BAC flow control, increasing by only 0.6 ºC on average. It was expected that the water temperature rise (range) in the BAC would not have changed significantly after implementation, similar to the performance of the condenser cooling tower observed previously. However, the average inlet water temperature increased slightly as a result of the evaporator flow control as reported in Table 26. If the BAC range stayed more or less constant then it can be expected that the average approach would increase slightly for similar ambient conditions as shown here.

Figure 110 shows the daily average water-side efficiencies and flow rates of the BAC for days with comparable ambient conditions.

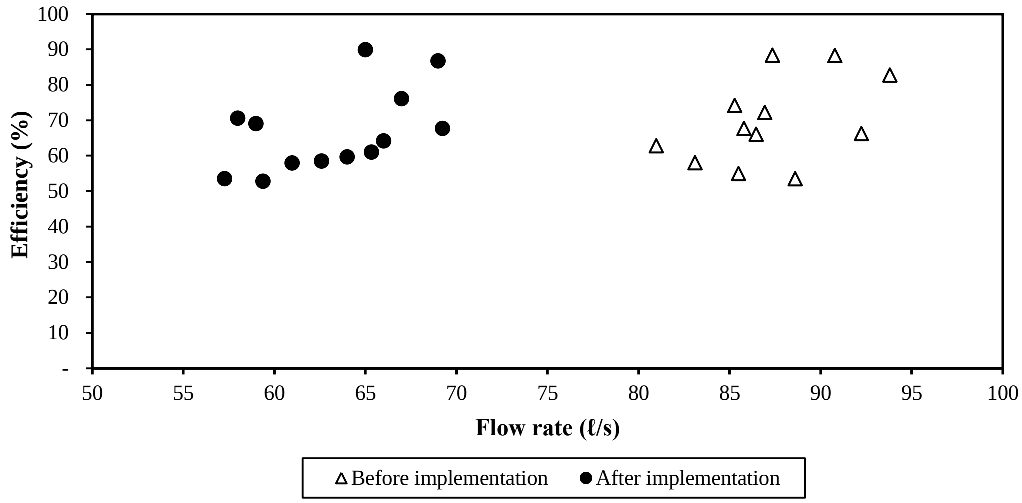

Figure 110 Daily average water-side efficiency of BAC as a function of total BAC water flow rate (Kusasalethu)

It is shown in Figure 110 that the average water-side efficiency of the BAC was not adversely affected by the lower flow rates, decreasing by only 4% after implementation. It would have been ideal to also calculate the air-side efficiencies of the BAC since its purpose is to cool the ventilation air. As with the other direct contact heat exchanger there are no psychrometric measurement sensors at the BAC outlet to provide historic data. However, it was noted in Table 26 that the ventilation air conditions remained constant at the underground Level 75 BAC inlet before and after implementation. The negligible changes in the BAC approach and water-side efficiency therefore confirm that the cooling of ventilation air was not adversely affected by the energy saving strategy. It also suggests that the air-side efficiency remained relatively constant.

It can be concluded that pre- and post-implementation water-side measurements indicate no decrease in the BAC cooling efficiency as a result of the reduced and controlled supply water flow rates. The Level 75 BAC air conditions showed no adverse effects and the BAC water-side efficiency decreased by only 4%. This indicates that, as discussed previously, the effective cooling of the ventilation air did not depend on the previous high flow rates and relied more on factors such as the BAC design and inlet temperatures of the air and water. It suggests that the original BAC supply flows were significantly over-designed. The BAC flow control in proportion to ambient enthalpy resulted in similar adequate cooling of the air without any BAC performance degradation.

8.4.6 Pumps

The effects of the strategies on the performance of the pumps were evaluated by considering the changes induced on the system and pump curves as suggested in Chapter 2.3. The pump efficiencies and operating points were experimentally determined and verified onsite by the pump manufacturer before and also after strategy implementation. Unfortunately, the mapped points of the system and pump curves cannot be published for confidentiality reasons. The key results are therefore only discussed here.

It has been mentioned that before implementation the pumps were over-specified and that design flows were achieved by variable opening valves on the discharge lines of the pumps. This method increased the system friction resistance to enable the lower flow rates. The system resistance curve was essentially raised, moving the pump duty point away from the most efficient operating point. By fully opening all valves at constant pump speed, the resistance curve was lowered significantly, moving the duty point further down and increasing the full speed pump efficiency by about 4%.

The Kusasalethu surface cooling system resistance depends largely on friction in the chiller heat exchangers and cooling towers (as opposed to static head-dominated systems). This means that the system resistance curve is similar in gradient to those of the pump iso-efficiency lines, as shown generically in Figure 12. By reducing the pump speed by VSD to again obtain the design flow, the duty point was seen to move along the system resistance curve at almost constant efficiency. The end result was an operational point giving the same design flow and sufficient pressure head as before implementation, but with a pump efficiency increase of about 2%. Further speed and flow reductions at partial load conditions decreased the pump efficiencies by a maximum of 3% from the original efficiency of about 81%. This was the worst case as observed for the evaporator pump group. The condenser and BAC pumps were less affected as a result of the lesser amount of pre-implementation flow restrictions.

No cavitation or related problems were observed during performance assessment and it is therefore assumed that the net positive suction head available was sufficient at the reduced flow rates. It was also found that the soft starting and stopping of the pumps were much better controlled by the VSDs than they had been when they were direct online. The negative direct online effects such as high inrush currents and large breakaway torques (leading to high mechanical stresses) were reduced considerably.

It can be concluded that pump efficiencies were only reduced by a maximum of 3% and that wear rates were not adversely affected as a result of the energy saving strategies at Kusasalethu.

8.4.7 Electrical system

The relative effects of the implemented energy saving strategy on the combined electrical reticulation system of the cooling system could not be evaluated by comparing pre- and post-implementation measurements, because the RFI and THD levels were not measured and trended by Kusasalethu before implementation. Therefore, these effects were only briefly evaluated by considering the relevant features (as described in Chapter 3.2) included in the VSD installations and by considering the general performance of the electrical system after implementation.

The VSDs installed at Kusasalethu as specified in Table 21 address high frequency RFI by including integrated EMC (electromagnetically compatible) filters in the drive. These EMC filters meet the relevant category C3 EN 61800-3 international standard, given that shielded power cables are provided and limited to 25 m in length per VSD (Schneider Electric 2010). The cables that were installed at Kusasalethu were shielded and the distances did not exceed 10 m. No RFI was apparent on any of the PLCs or similar equipment in the vicinity of the cooling system substations where the VSDs were installed. It is thus assumed that the RFI levels in the integrated system were kept sufficiently low by the EMC filters.

The specified VSDs address low frequency harmonics by the inclusion of standard line chokes in the VSD panel installed just upstream in the power supply. They serve a dual purpose in that they protect the drive from overvoltage and also reduce the THD introduced back into the power supply system.

The specified line chokes comply with standard IEC 61800-5-1 and reduce THD to a maximum level of 35% (Schneider Electric 2010). When the drives were specified the mine personnel indicated that this would be sufficient. The cooling system did not have any pre-implementation THD problems.

During the three months after implementation there were no apparent THD problems on any of the electrical systems of the cooling system. It is believed that the line chokes reported filtering capabilities were sufficient, as suggested by the mine personnel. The VSDs were also connected to power supply transformers without many other systems connected to the same power supply line. Transformers usually filter out harmonics further so it is advisable to connect the VSDs as was done at Kusasalethu.

If harmonic distortion does become apparent later, it would be possible to install an external passive filter to the existing VSDs. For the specified units, these will further reduce the THD levels to below 5%, should this be a requirement (Schneider Electric 2010).

A general performance assessment of the overall electrical system during the three months after implementation did not reveal any degradation as a result of the implemented strategies. There were no significant cases of short circuits, burnouts, cable overheating, power factor reductions or voltage and current supply problems. This further indicates that, as far as could be determined, the VSD installations and the newly implemented control strategies did not adversely affect the existing electrical system in any way.

8.4.8 Combined cooling system

The effect of the energy saving strategies on the integrated performance of the combined cooling system was evaluated by the global COP as defined by Equations 7 to 9. As discussed in Chapter 2.6, the thermal load considered is the total load of the integrated cooling system and the input power includes all electrical energy users such as chiller compressors, water pumps and cooling tower fans.

Figure 111 (Du Plessis et al. 2013b) shows the daily average global COP values before and after implementation as well as the associated thermal load of the combined cooling system.

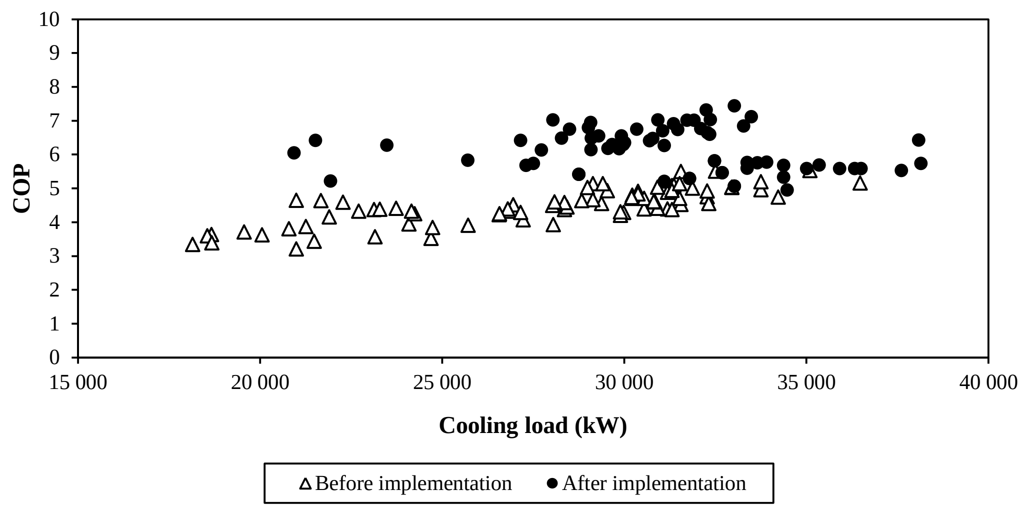

Figure 111 Daily average global COP of combined cooling system (Kusasalethu) (Reprinted from *A versatile energy management system for large integrated cooling systems*, Du Plessis G.E., Liebenberg L., Mathews E.H., Du Plessis J.N., Energy Conversion and Management, 66, 312-325, Copyright (2013), with permission from Elsevier)

It is shown in Figure 111 that although the combined cooling loads remained within the same range, the combined plant COP increased by 36%. This result is in effect a summary of the results discussed in Chapters 8.2 and 8.3. It shows that the cooling load of the entire plant, or the overall service delivery, was not compromised while the total electrical input to realise that cooling was 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 power input, whether the load is caused by large water volume demands, high inlet temperatures or high ambient psychrometric conditions. The larger COP increases are shown for typical thermal loads below about 33 MW. This shows that as the load on the system decreases, the potential to realise part-load savings by matching the water supply to the demand increases.

It can thus be concluded that although the overall cooling load on the integrated surface cooling system remained within the same range, the methods of achieving the required cooling became significantly more energy efficient. This is due to the lower daily cooling demand on the chillers caused by no water recirculation, lower chilled water demands required by the BAC, the more efficient pre-cooling towers and the reduced energy requirements of the various pumps.

This efficiency improvement was more pronounced on days when the overall cooling load was lower than design. In general, the essential concept of the variable-flow strategy matching the cooling supply to its demand was shown to be effective.

8.4.9 Summary

A summary of all the key results regarding system and subsystem performance is given in Table 27.

Table 27 Summary of the effects on cooling system performance (Kusasalethu)

	Result		
New control strategies			
Evaporator flow control	Maintained chilled water dam level at 90-100%		
Condenser flow control	Maintained condenser water temperature rise at 4-5 ºC		
BAC supply water control	Supplied BAC water at 50-70 ℓ/s		
BAC return water control	Maintained BAC drainage dam set point within 0.26%		
	Before implementation	**After implementation**	**Change (%)**
Chillers			
COP of chillers 1 and 2 in series	5.8	5.7	-1.1
COP of chillers 3 and 4 in series	5.9	5.8	-1.5
Number of total tripped conditions	8	6	-25
Pre-cooling towers			
Water-side efficiency (%)	50	78	56
Water temperature drop in pre-cooling tower (ºC)	5.5	8.7	58
Condenser cooling tower			
Water-side efficiency (%)	20	29	46
Bulk air cooler			
Water-side efficiency (%)	70	67	-4
Water pumps			
Evaporator pump efficiency (%) [largest change]	81	78-83	-3.7 to 2.5
Electrical system			
RFI (%)		Sufficiently low	-
THD (%)		< 35	-
Combined cooling system			
Global COP	4.5	6.1	36

It can be concluded from Table 27 that the system performance of the integrated Kusasalethu surface cooling system was not adversely affected. The implementation of the developed variable water flow strategy and its energy management system therefore did not interfere significantly with the performance of the Kusasalethu cooling system or its subsystems and can be considered as a viable retrofit to the existing system.

8.5 Economic viability

The economic feasibility of the DSM strategy for Kusasalethu was discussed in detail as part of the pre-implementation cost-benefit analysis in Chapter 6.5. The incurred costs remained the same during implementation as reported previously. However, the savings that were realised have been shown to be more than predicted during the simulation in Chapter 6. The associated cost savings were therefore also more than used during the original analysis. This section serves as an update of the realised economic viability indicators, using the actual achieved energy cost savings and costs. These updated results also form part of Appendices C.1 and D.1 (Du Plessis et al. 2013a and 2013b). The same parameters and analyses were considered as discussed in Chapter 6.5.

It is conservatively assumed that the achieved average saving of 2 609 kW (35.4%) will be realised for the remaining nine months of the year. Using the average realised daily saving profile and the most recent electricity tariffs as given in Table 18, the actual annual cost saving amounts to R9 669 996. The previously shown implementation cost remained at R5 241 322.

The cost of conserved energy amounts to R227/MWh, which is lower than predicted before implementation. The payback period realised was calculated to be seven months, a month less than originally predicted. The IRR was found to be 188% and the 15% NPV was R67 813 299. The shown indicators are all improved values of the calculations shown in Chapter 6.5 and therefore prove the definite economic feasibility of the DSM strategy after implementation. These figures are published in Annexure C.1 (Du Plessis et al. 2013b) for the parallel-series chiller system (i.e. Kusasalethu).

It is worth mentioning that the economic indicators shown in Annexure D.1 (Du Plessis et al. 2013a) are slightly less, indicating an annual saving of R6 700 000 and a payback period of 8.6 months. This is because only one month of *in situ* results and its associated cost benefits were available at time of publication, as mentioned previously.

It can be concluded that the updated economic feasibility indicators based on actual achieved savings emphasise the economic viability of the developed variable water flow strategy implemented at Kusasalethu.

8.6 Conclusion

It was shown that the developed energy saving strategy realised significant savings when implemented on the primary case study surface cooling system of Kusasalethu. For three months of performance assessment, an average daily electrical energy saving of 2 609 kW, or 35.4% of the baseline power was realised. The total saving comprised direct evaporator, condenser and BAC pump savings as well as the saving resulting from a large reduction in daily water volume that needed to be chilled by the chillers. This water volume reduction resulted from the BAC supply water flow control and the combined effect of shutting off the chilled water back-pass line, installing new pre-cooling towers and controlling the evaporator water flow rate to maintain the specified chilled water dam level.

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

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

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

It is concluded from the measured and verified *in situ* experimental results that the proposed variable water flow strategy and its developed energy management system were proven successful.

Significant energy savings were realised without compromising service delivery or system performance when implemented on the Kusasalethu mine cooling system as a primary case study. The experimental investigation therefore validated the developed DSM strategy as a viable new energy saving method on large cooling systems as found on deep mines. To add confidence to the reported success of the strategy and to validate its versatile applicability to various large cooling systems, further case study results are briefly considered in the next chapter.