

CHAPTER 4

VERIFICATION OF THE ENERGY MANAGEMENT SOLUTION

4.1 Preamble

The developed Energy Management System (EMS) was implemented on ten mine compressor systems. EMS was implemented on basic as well as intricate compressor systems to assess the scalability of the solution. A basic compressor system consists of several compressors at the same geographical location. An intricate system consists of compressors, at different locations, supplying compressed air to the same compressed-air network.

Due to the importance of uninterrupted compressed-air supply, automatic compressor stopping, starting, loading and unloading were not allowed by any of the mines. These control actions were however initiated manually by the operator, based on the onscreen EMS schedules.

4.2 Impact measurement

4.2.1 Baselines

Before implementation of EMS, three months of pressure and power measurements are gathered. Pressure measurements are collected from pressure transmitters, installed at each shaft. Portable power loggers are used to compile individual compressor power consumption data during the three-month period.

This data is used to establish individual pressure and power consumption baselines for an average weekday, Saturday and Sunday. These baselines are 24-hour profiles. Individual baselines are established for the three production-day types because the production schedules differ for each of these days. Maximum production is typically scheduled for weekdays, with lighter schedules on Saturdays and no production on Sundays.

4.2.2 Impact

After implementing EMS, the actual pressure and power measurements are logged. The data for each day is processed into 24-hour profiles and compared to the 24-hour pressure and power consumption baselines. This is done in order to determine the impact of EMS.

To quantify the impact, the average reduction in electricity consumption is calculated for the individual production days. In addition, the average electricity cost reduction is calculated using the TOU billing structure. These averages are interpolated to a typical month; consisting of 22 weekdays, four Saturdays and four Sundays.

Cost calculations are based on Eskom tariff structures for 2009/2010 [12]. In this document, the Eskom low demand season is referred to as summer, and extends from September to May. The high demand season is referred to as winter, and extends from June to August.

4.3 Case study: Basic compressed-air system

4.3.1 Overview of compressed-air system

EMS was implemented at a platinum mine (Mine A). This mine has a basic compressed-air system consisting of seven compressors. These compressors supply compressed air to three of the four shafts at the mine. The schematic diagram of the surface compressed-air system is shown in Figure 4-1.

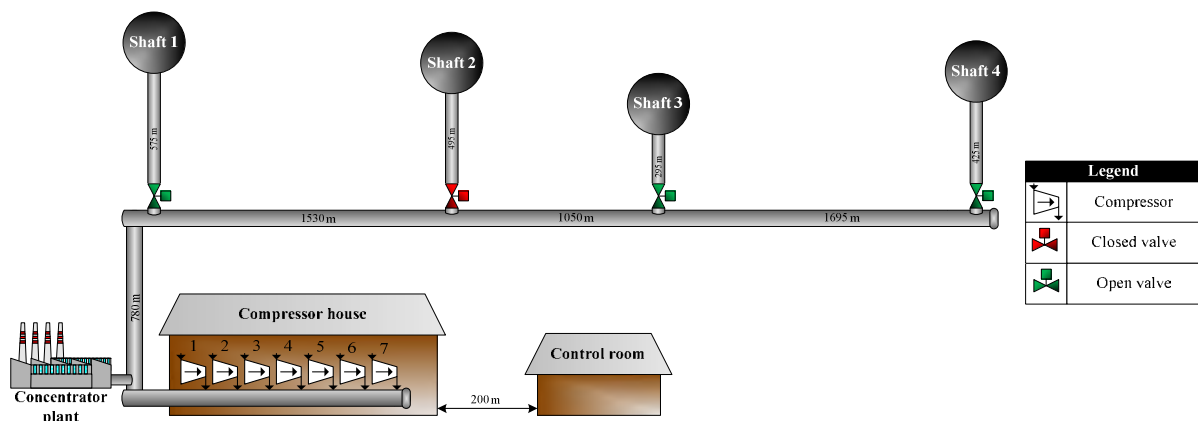


Figure 4-1: Mine A surface compressed-air system layout

The seven compressors are identical, with electrical capacities of 2.6 MW each. The total installed electrical capacity of the compressor system is 18.2 MW. Air is supplied to the various shafts via a compressed air column that runs past the shafts. Shaft 2 is isolated from the main column and does not require any compressed-air.

At this mine, manual compressor energy management has already been implemented. This was however done without pressure feedback from the compressed-air system. The typical weekday power consumption of the compressors, before implementation of EMS, is shown in Figure 4-2.

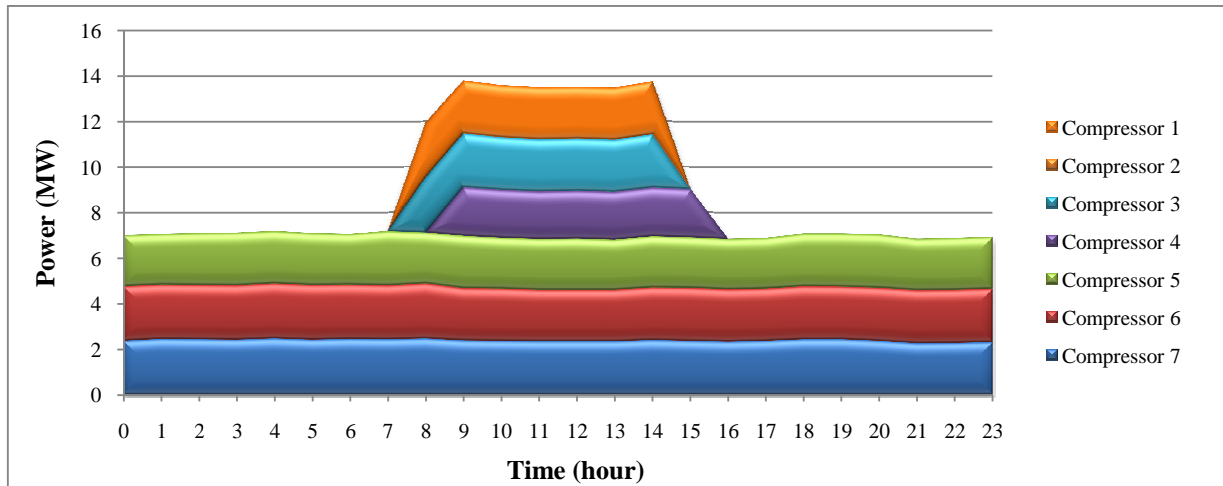


Figure 4-2: Typical pre-implementation compressor operation at Mine A

Baseload compressors (Compressor 5, 6 and 7) are running constantly, and additional trimming compressors (Compressor 1, 3, and 4) are started up to ensure that the pressure can be sustained throughout the production shift from 7:00 to 15:00. This compressor control strategy is the result of years of trial and error.

4.3.2 Implementation

An inspection of the site revealed that an iFix SCADA system was installed. The compressors were already fitted with measurement instrumentation. Compressor temperature transmitters were however found to be faulty and HMI control panels were damaged. After assessing the existing compressor control system, it was found that the following modifications were required:

- Replace seven discharge pressure transmitters
- Recalibrate all the existing instrumentation
- Upgrade SCADA software to the latest version
- Additional SCADA tag licensing
- Additional I/O box

Flow- and pressure-transmitter pairs were installed on the surface air network at Shaft 1, Shaft 3 and Shaft 4. The flow and pressure measurements at the various shafts are transmitted to the SCADA system via outdoor wireless points, installed at each shaft and the control room. This wireless network, together

with the existing communication between the compressor house and the control room, are shown in Figure 4-3.

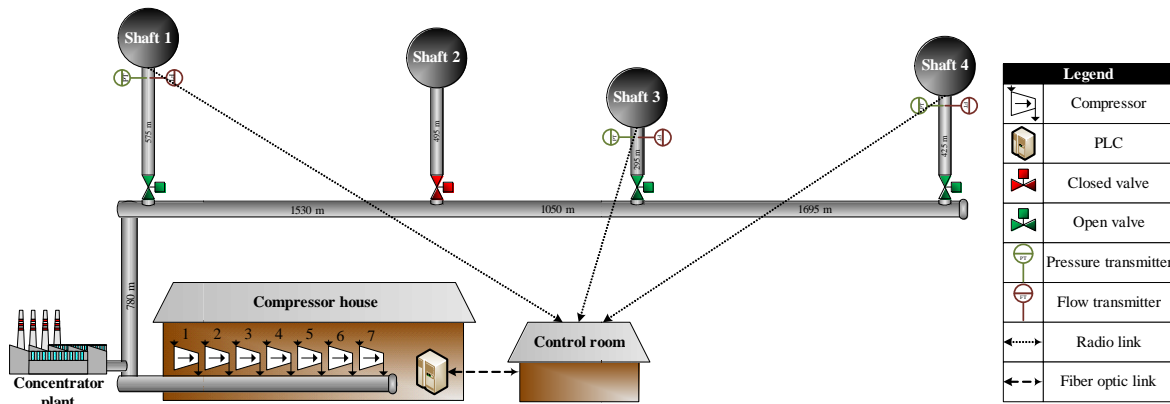


Figure 4-3: Mine A communication infrastructure

Communication between the compressor instrumentation and the PLC is achieved with the use of RS-422 (Recommended Standard 422) twisted pair cables. An existing Ethernet network is used to facilitate communication between the PLC and SCADA system. The EMS software establishes an OPC connection with the SCADA system. Compressor control is achieved with the software-modelled surface compressed-air system shown in Figure 4-4.

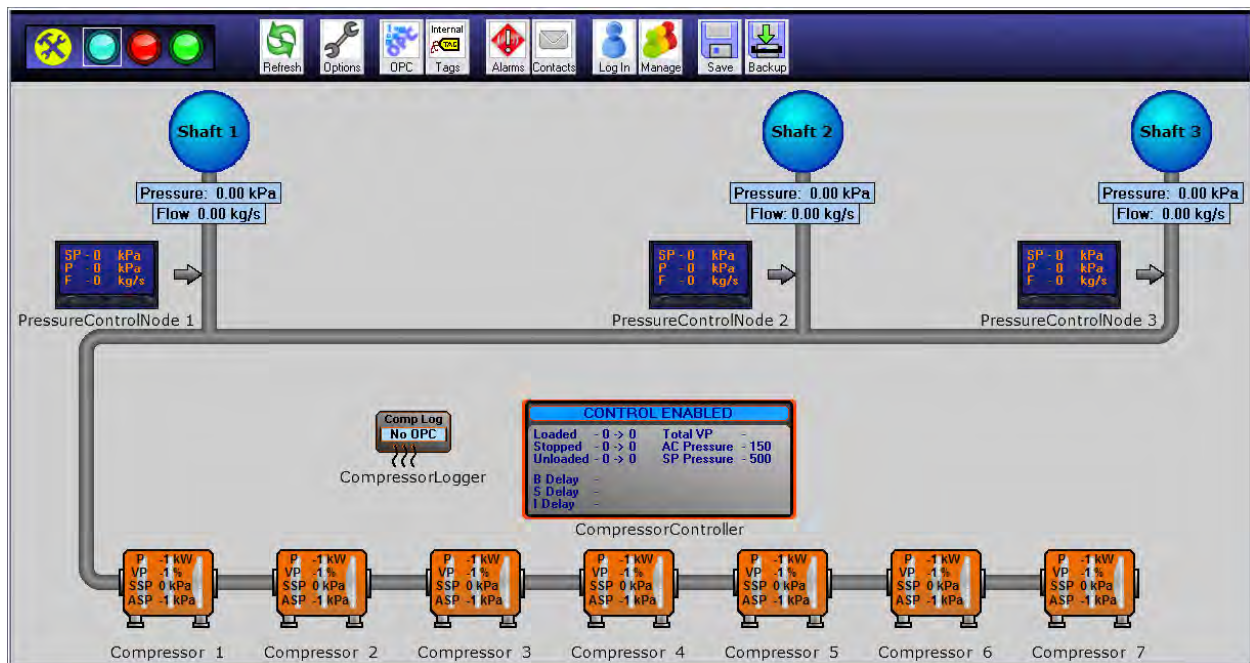


Figure 4-4: Modelled surface compressed-air system of Mine A

From this GUI the software user has full control over all the compressors. Measurements from the installed pressure and flow transmitters are displayed onscreen and updated in real-time. The results for this case study are based on data logged by the EMS software over a period of nine months.

4.3.3 Results

Optimised compressor operation

After implementation, compressor control consisted of stopping, starting, loading and unloading, in addition to capacity control. Figure 4-5 shows the effect of capacity control, starting, stopping and unloading on the power consumption of a specific compressor over a 24-hour period.

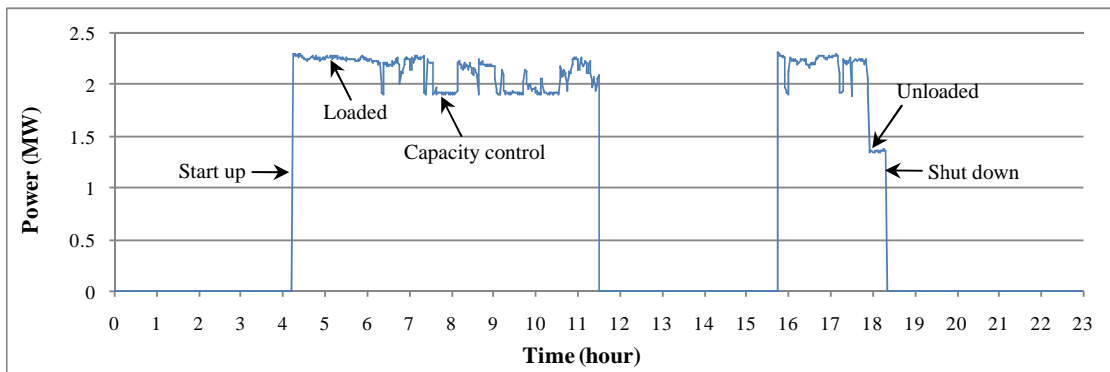


Figure 4-5: Compressor control at Mine A

For this specific compressor, the no-load power consumption is approximately 60% of the full-load power consumption.

The layer chart in Figure 4-6 shows the typical compressor operation after implementation of EMS. Changes in compressor operation become apparent when comparing Figure 4-6 with Figure 4-2.

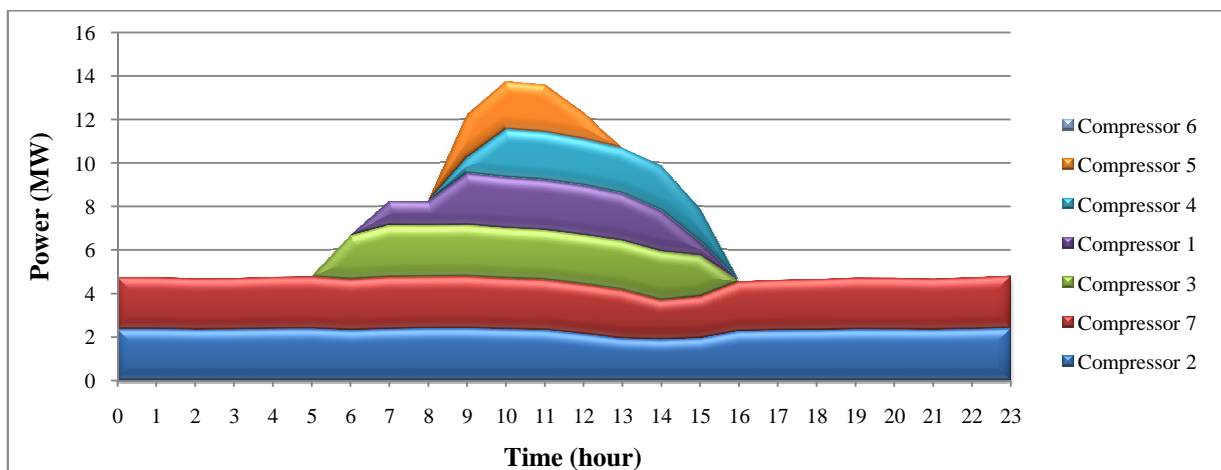


Figure 4-6: Typical post-implementation compressor operation at Mine A

On a typical weekday, two compressors are used as baseload compressors, compared to the three baseload compressors before implementation. Trimming compressors are running for a shorter period of time, during the peak-production shift, than before implementation. Optimisation of compressor operation was

possible because of real-time feedback from the pressure transmitters at each of the active shafts. This feedback allows EMS to closely match the supply pressure with demand.

Impact on system pressure

A distinct drop in the weekday and Saturday pressure baselines are observed. This drop is due to peak air consumption during the production shifts, as indicated in Figure 4-7(a) and (b).

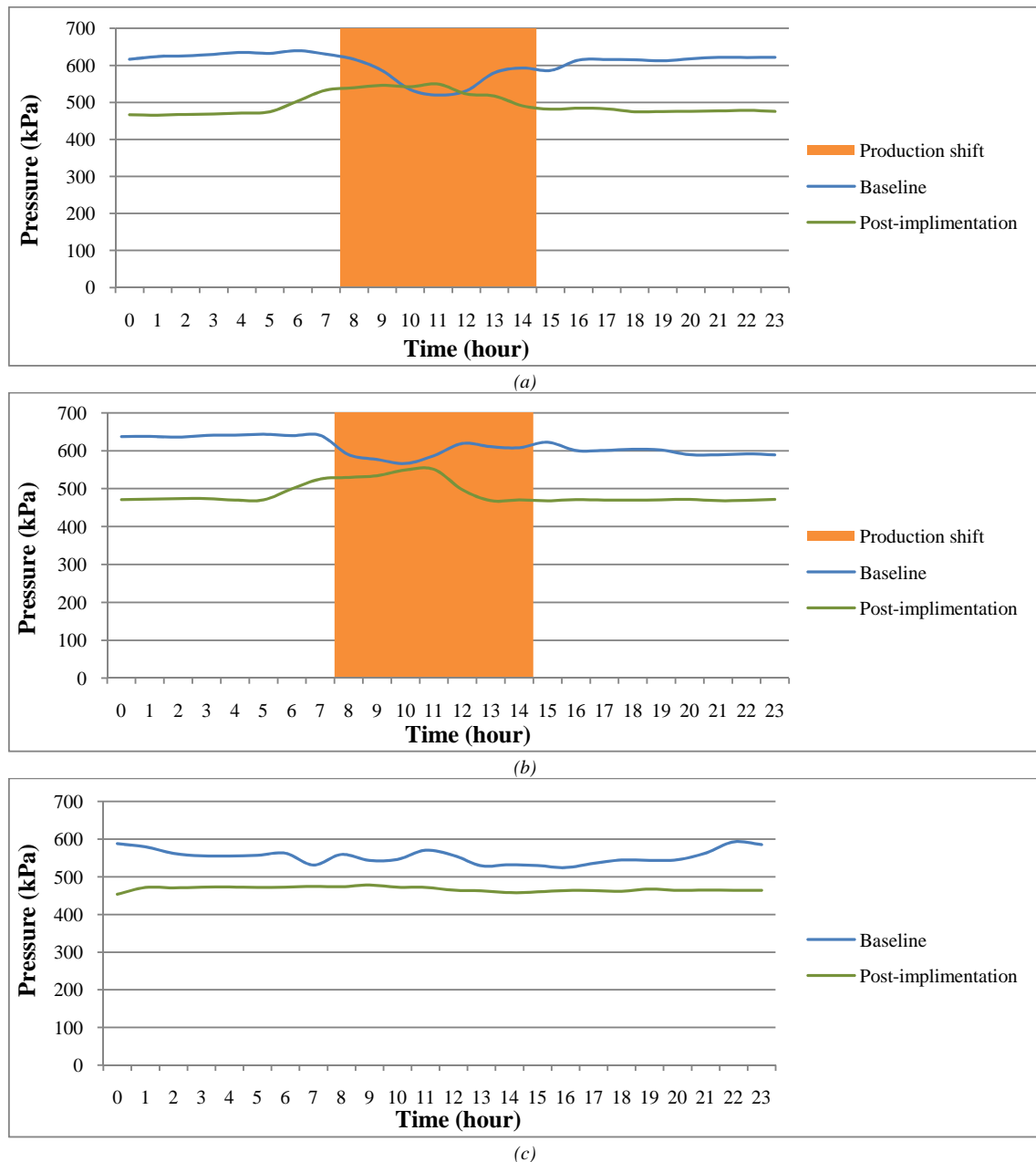


Figure 4-7: Impact on system pressure at Mine A for the average (a) weekday, (b) Saturday and (c) Sunday

Compensation for the increased demand for air during production shifts is indicated on the post-implementation profiles in Figure 4-7(a) and (b). The average Sunday pressure baseline is compared with

the post-implementation pressure profile in Figure 4-7(c). EMS ensured that the system pressures are maintained at a significantly lower level than the baseline pressures of all three the production-day types.

Impact on compressor power consumption

Reduced pressure profiles in Figure 4-7 are achieved by optimised compressor operation. This results in a reduction in the compressor system electrical energy consumption. Figure 4-8(a), (b) and (c) show comparisons of the baselines with the average weekday, Saturday and Sunday power consumption profiles respectively.

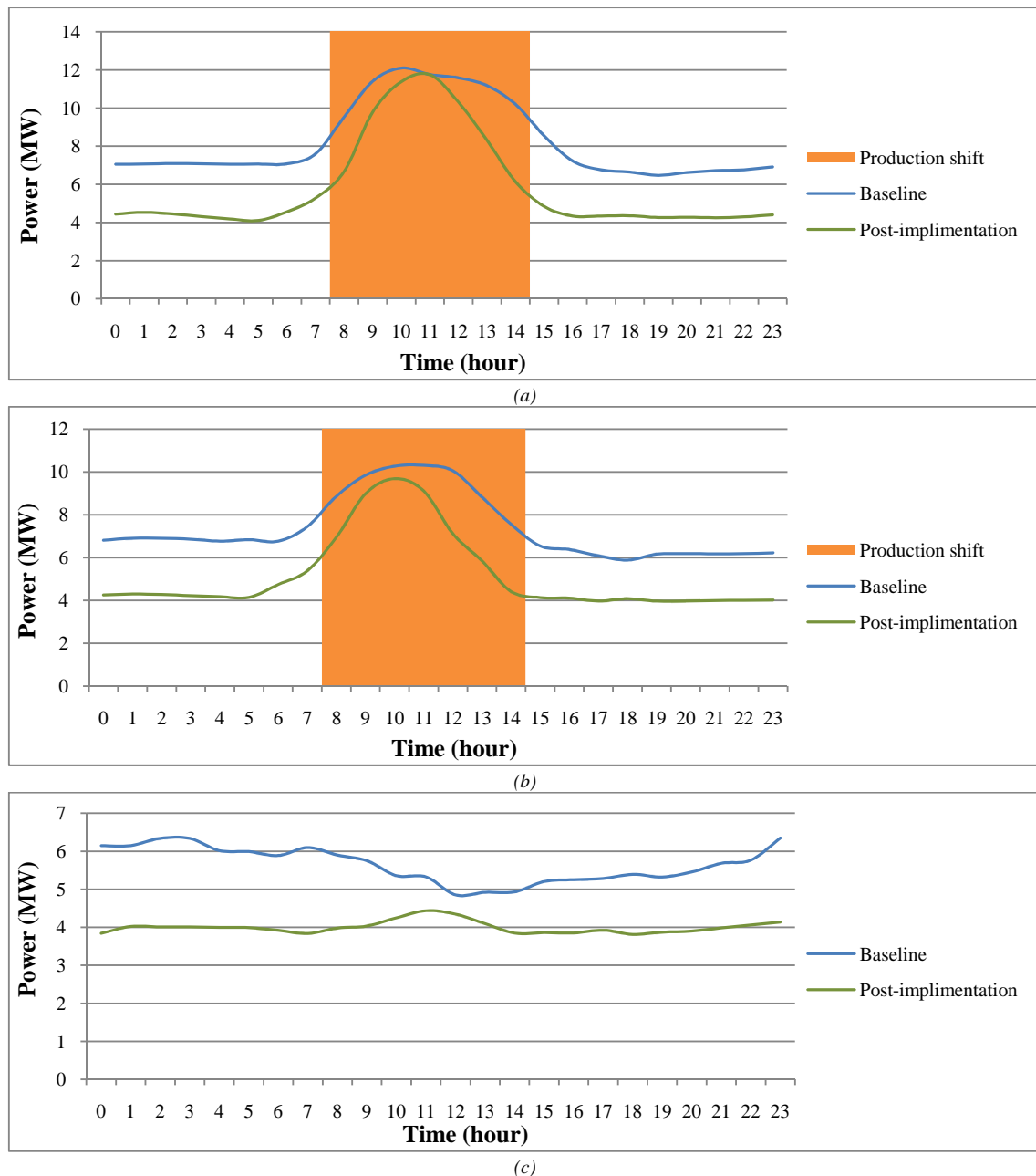


Figure 4-8: Impact on power consumption at Mine A for the average (a) weekday, (b) Saturday and (c) Sunday

From Figure 4-8(a) it is clear that the existing compressor control strategy reduced unnecessary compressor operation during the low-demand time of the day. The opportunity did however exist to improve the control strategy to achieve a further electrical efficiency during low-demand periods. The power consumption profiles in Figure 4-8(b) and (c) show a significant efficiency improvement compared to the baseline profiles.

Measurement of impact

To quantify the impact EMS had on the electrical energy consumption and cost, the post-implementation profiles are deducted from the baseline profiles in Figure 4-8(a), (b) and (c) respectively. The obtained profile is used to calculate the total impact on the electrical energy consumption and electrical energy cost. Table 4-1 shows the calculations for an average weekday.

Table 4-1: Average weekday power and electricity cost reduction at Mine A

Hour	Baseline (kW)	Actual (kW)	Impact (kW)	Summer		Winter	
				Cost per kWh (c/kWh)	Impact (R)	Cost per kWh (c/kWh)	Impact (R)
0	7,049	4,439	2,610	15.72	410	18.25	476
1	7,062	4,532	2,530	15.72	398	18.25	462
2	7,090	4,448	2,642	15.72	415	18.25	482
3	7,078	4,312	2,766	15.72	435	18.25	505
4	7,055	4,185	2,870	15.72	451	18.25	524
5	7,059	4,104	2,955	15.72	465	18.25	539
6	7,072	4,561	2,511	22.48	564	34.17	858
7	7,598	5,279	2,318	36.70	851	131.43	3,047
8	9,534	6,675	2,859	36.70	1,049	131.43	3,758
9	11,406	9,790	1,617	36.70	593	131.43	2,125
10	12,101	11,378	723	22.48	163	34.17	247
11	11,760	11,748	12	22.48	3	34.17	4
12	11,587	10,311	1,275	22.48	287	34.17	436
13	11,180	8,315	2,865	22.48	644	34.17	979
14	10,197	6,134	4,063	22.48	913	34.17	1,388
15	8,544	4,846	3,699	22.48	831	34.17	1,264
16	7,222	4,337	2,885	22.48	649	34.17	986
17	6,757	4,337	2,419	22.48	544	34.17	827
18	6,643	4,350	2,292	36.70	841	131.43	3,013
19	6,468	4,259	2,208	36.70	811	131.43	2,903
20	6,615	4,272	2,343	22.48	527	34.17	801
21	6,715	4,251	2,464	22.48	554	34.17	842
22	6,763	4,292	2,471	15.72	388	18.25	451
23	6,912	4,401	2,511	15.72	395	18.25	458
Total	197.4 kWh	139.5 kWh	57.9 kWh		R 13,181		R 27,374

The same calculations are done for an average Saturday and Sunday and the results are interpolated to obtain average monthly results. The results of these calculations are summarised in Table 4-2.

Table 4-2: Summary of impact at Mine A

Average	Baseline (MWh)	Impact (MWh)	Summer impact (R)	Winter impact (R)
Weekday	197	58	13,181.00	27,374.00
Saturday	176	53	9,054.00	11,369.00
Sunday	135	40	6,235.00	7,239.00
Monthly	5,594	1,645	351,131.00	676,651.00

The bar chart in Figure 4-9 shows the comparison of the summer and winter cost reduction for an average weekday, Saturday and Sunday.

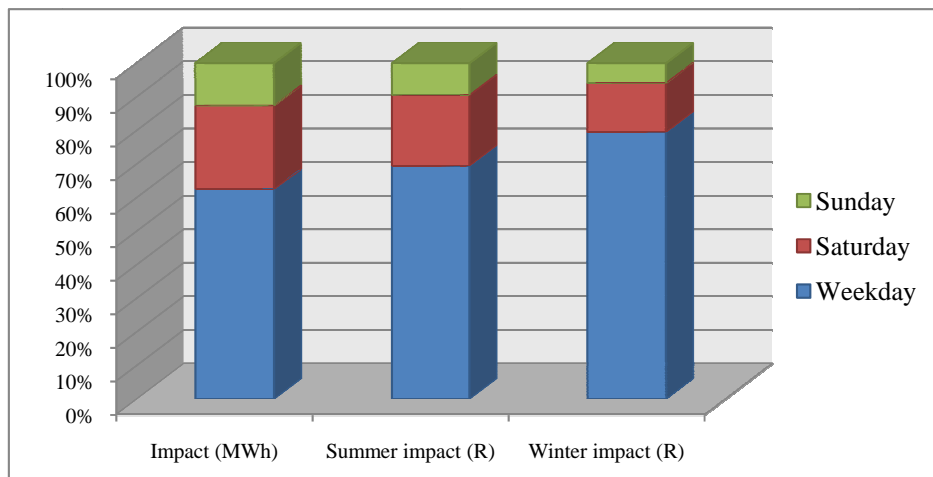


Figure 4-9: Comparison of impact on typical weekday, Saturday and Sunday at Mine A

When calculating the electricity cost reduction, the TOU structure discussed in Section 1.2.3 causes average weekday cost reduction to be substantially more than for an average Saturday or Sunday. This cost difference is further increased by the more expensive winter tariffs as shown in Figure 4-9.

4.4 Case study: Intricate compressed-air system

4.4.1 Overview of compressed-air system

EMS was implemented at a gold mine (Mine B). The surface compressed-air system consists of three mining shafts. These shafts are supplied by compressors from three compressor houses, one at each shaft. The schematic of this compressed-air system is shown in Figure 4-10.

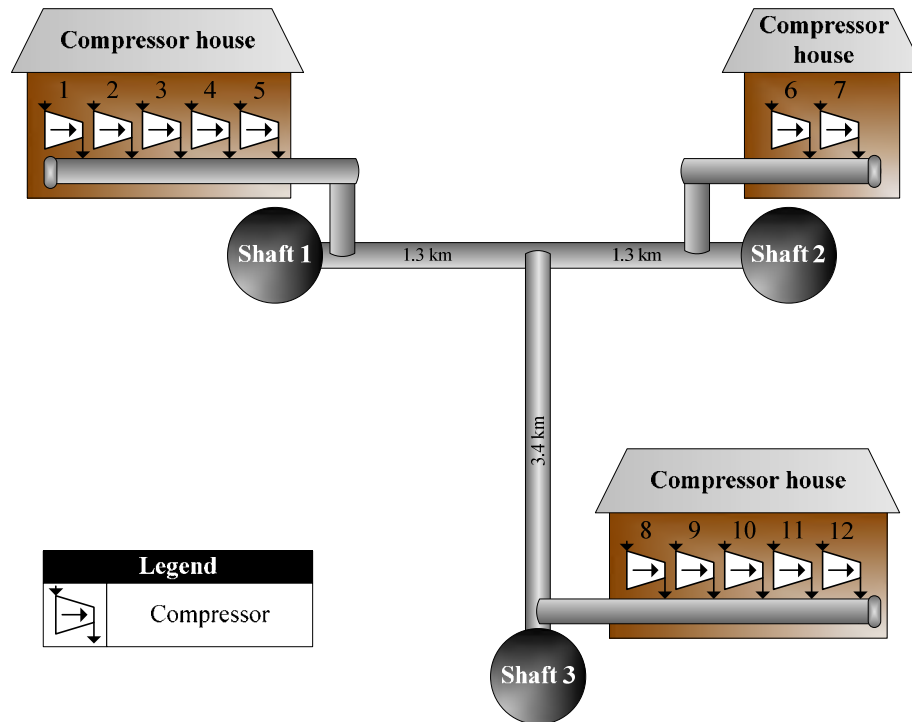


Figure 4-10: Mine B surface compressed-air system layout

The three shafts were however functioning independently, with the air network closed off between them. In total, the compressor system consists of twelve compressors. The rated electrical capacities of the compressors are shown in Table 4-3.

Table 4-3 : Compressor specifications for Mine B

Shaft	Compressor name and brand	Rated capacity (MW)
1	Compressor 1 – BTH	3.7
	Compressor 2 – BB	4.0
	Compressor 3 – BB	4.0
	Compressor 4 – BB	4.0
	Compressor 5 – Sulzer	4.8
2	Compressor 6 – Sulzer	5.9
	Compressor 7 – Sulzer	5.9
3	Compressor 8 – Sulzer	5.4
	Compressor 9 – Sulzer	5.4
	Compressor 10 – Sulzer	5.4
	Compressor 11 – Sulzer	5.4
	Compressor 12 – Sulzer	5.4
Total		59.4

The total installed electrical capacity of the compressor system is 59.4 MW.

4.4.2 Implementation

A site visit to Mine B revealed that none of the compressors were automated and because of this, several main compressors were running continuously. Additional standby compressors were only started up during maintenance on the main compressors. There was no existing communication infrastructure between the compressor houses and the control room. The implementation phase of the project included:

Compressor control instrumentation

- Individual compressor PLCs with HMI panels
- Moore anti-surge controllers (PAC 353 Basic controller)
- Upgrade blow-off valves
- Inlet throttle-valve installations

Measurement instrumentation

- Pressure transmitters
- Vibration transmitters
- Temperature transmitters
- Proximity probes

Lubrication and cooling system instrumentation

- Automation of water-cooling pumps
- Automation of water-cooling fans

Compressed-air network

- Reopen air network to connect all three shafts

SCADA system (Archestra)

- Development and commissioning

All the compressors were instrumented for full automation and the network infrastructure — linking the three compressor houses with the control room — was installed.

The Orchestra SCADA system is situated in a centralised control room. The EMS software establishes an OPC connection to this SCADA system and compressor control is achieved with the modelled surface compressed-air system as shown in Figure 4-11.

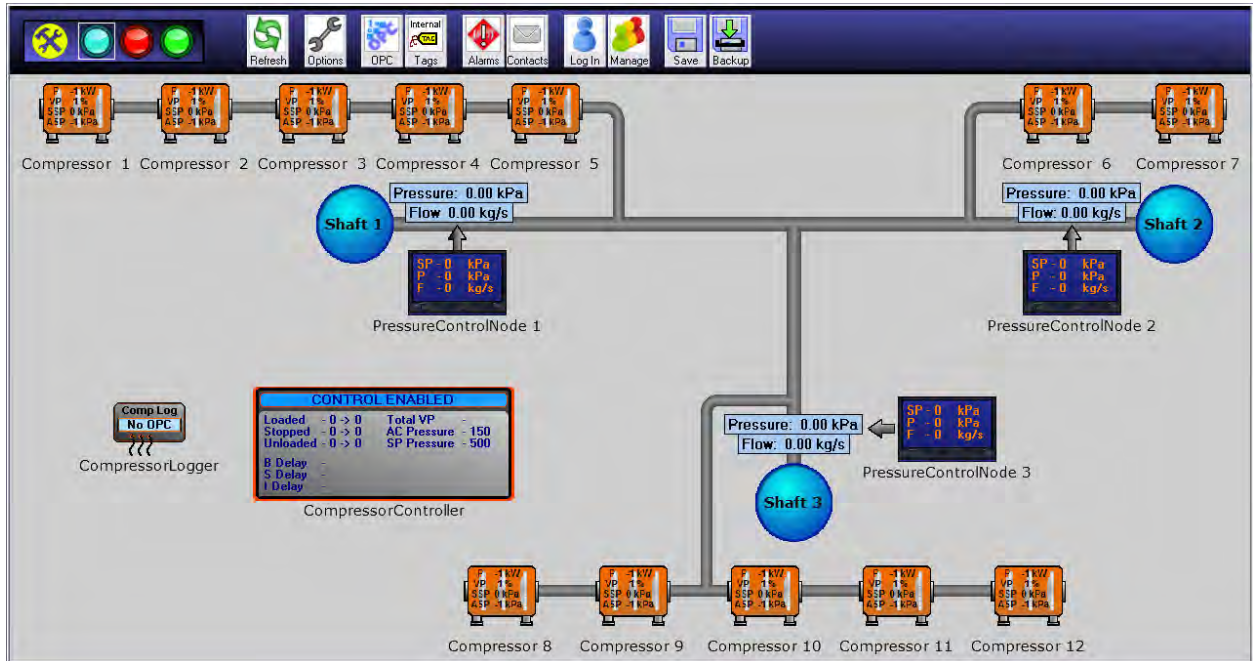


Figure 4-11: Modelled surface compressed-air system of Mine B

The EMS software GUI allows for remote control of all the compressors. Real-time measurements from pressure and flow transmitters are displayed onscreen. The results of the case study on Mine B are based on data logged by the EMS software over a period of six months.

4.4.3 Results

Optimised compressor operation

After implementation, compressor control consisted of stopping, starting, loading and unloading in addition to capacity control. Figure 4-12 shows the power consumption and inlet throttle-valve positions of a specific compressor, over a 24-hour period.

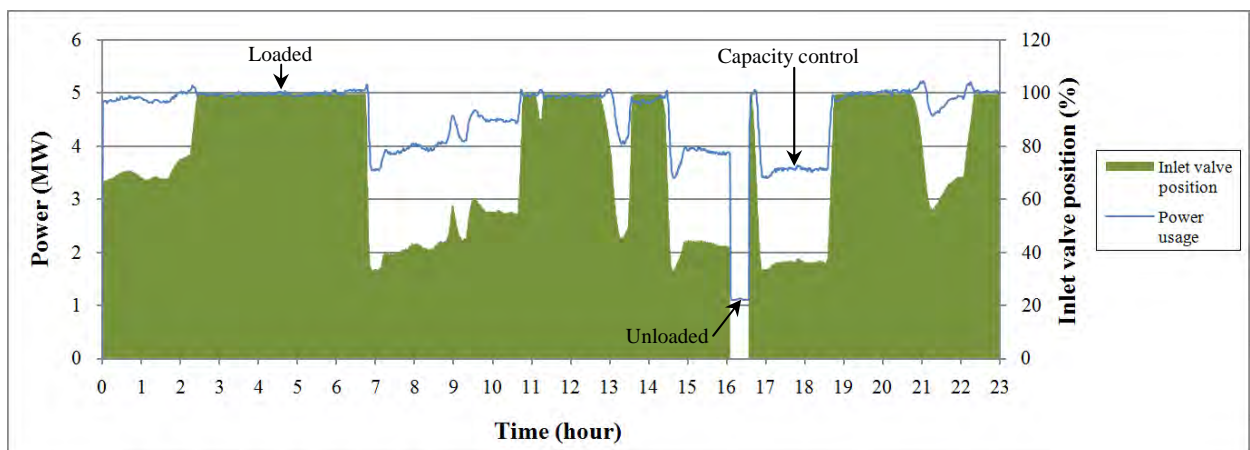


Figure 4-12: Compressor control at Mine B

When the inlet throttle-valve opening is reduced, the compressor capacity is reduced. This control change results in a reduction in compressor power consumption as indicated in Figure 4-12. By closing the inlet throttle valve and opening the blow-off valve, the compressor is unloaded as indicated in Figure 4-12. On this specific compressor, the no-load power consumption is approximately 20% of the full-load power consumption. The reduction in power consumption, due to unloading a compressor, was found to vary significantly for different compressors.

The layer chart in Figure 4-13 shows the typical weekday compressor operation after implementation of EMS. Optimisation of compressor control was possible because there was no control strategy implemented at this mine.

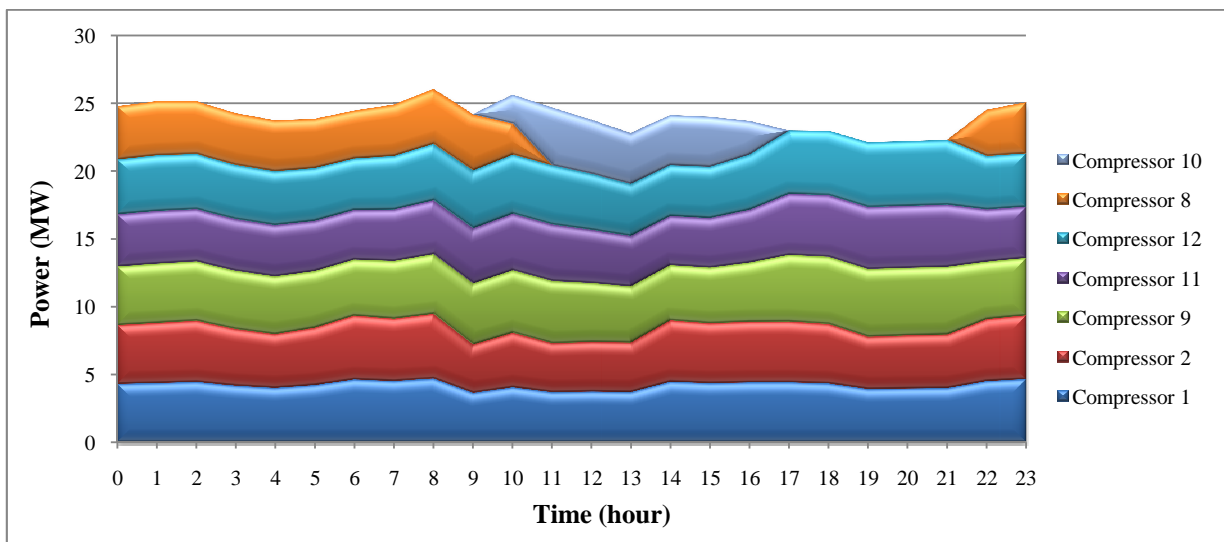


Figure 4-13: Typical post-implementation compressor operation at Mine B

In addition to optimised compressor operation, the compressed-air network between the shafts was reopened in order to allow all the compressors to supply air to a common air system. This allowed for sufficient air supply to all the shafts with a reduced number of running compressors and reduced blow-off of excessive compressed air.

Impact on system pressure

Pressure baselines were constructed for each mining shaft. These baselines were combined to obtain the pressure baseline for Mine B. Comparisons of the pressure baseline and post-implementation pressure profiles for a weekday, Saturday and Sunday are shown in Figure 4-14(a), (b) and (c) respectively.

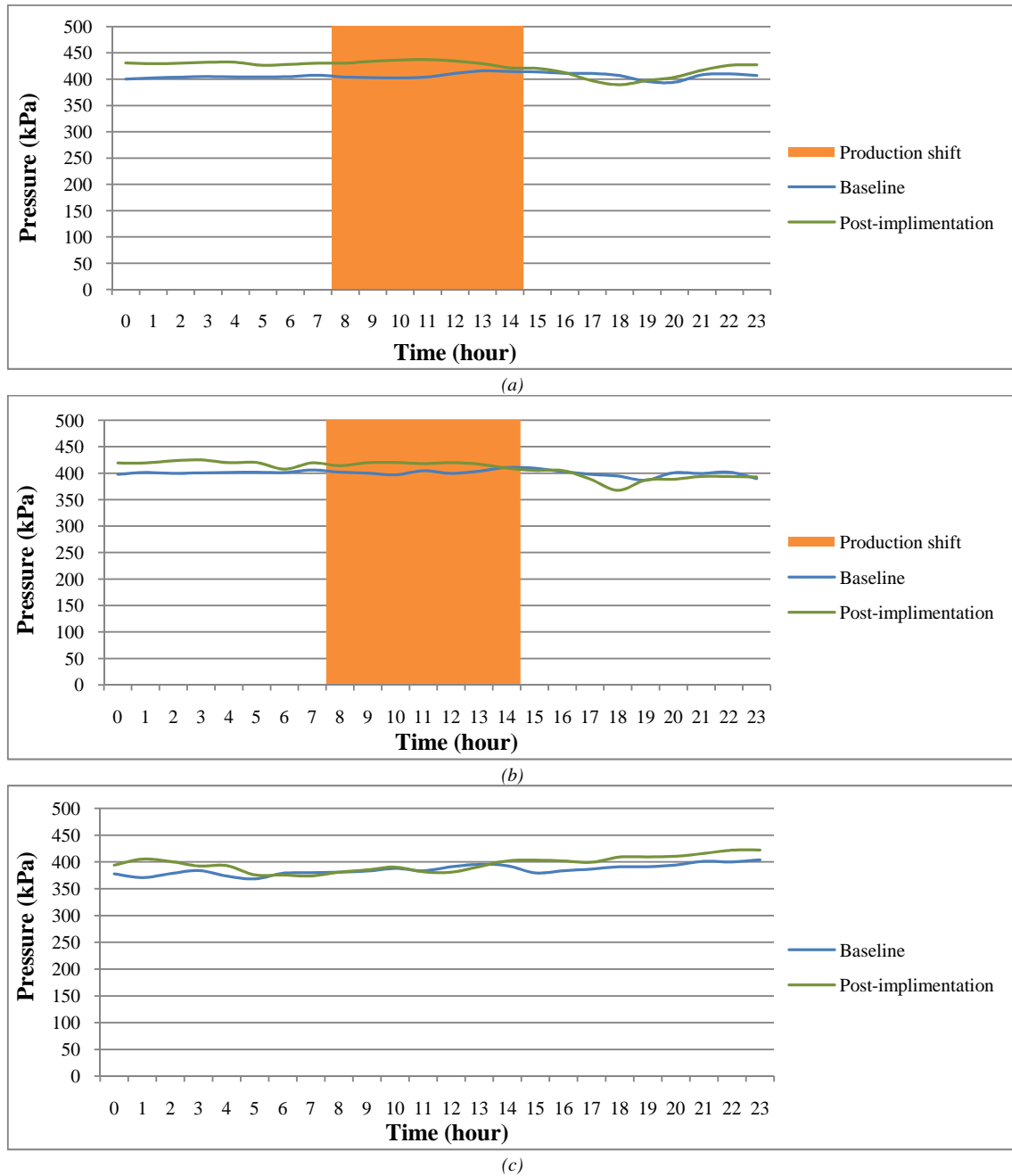


Figure 4-14: Impact on system pressure at Mine B for the average (a) weekday, (b) Saturday and (c) Sunday

The post-implementation pressure is maintained noticeably higher than the baseline pressure. This is the expected result from opening up the air network to allow more even distribution of compressed air according to demand, thus improving the efficiency of the compressed-air system.

Impact on total compressor power consumption

Increasing compressed-air system efficiency without reducing the system pressure was not expected to result in significant electrical efficiency. By operating the most efficient compressors as baseload

compressors and introducing active capacity control on trimming compressors, the supply is more closely matched with the demand. This however resulted in significant electrical energy efficiency as shown in Figure 4-15(a), (b) and (c).

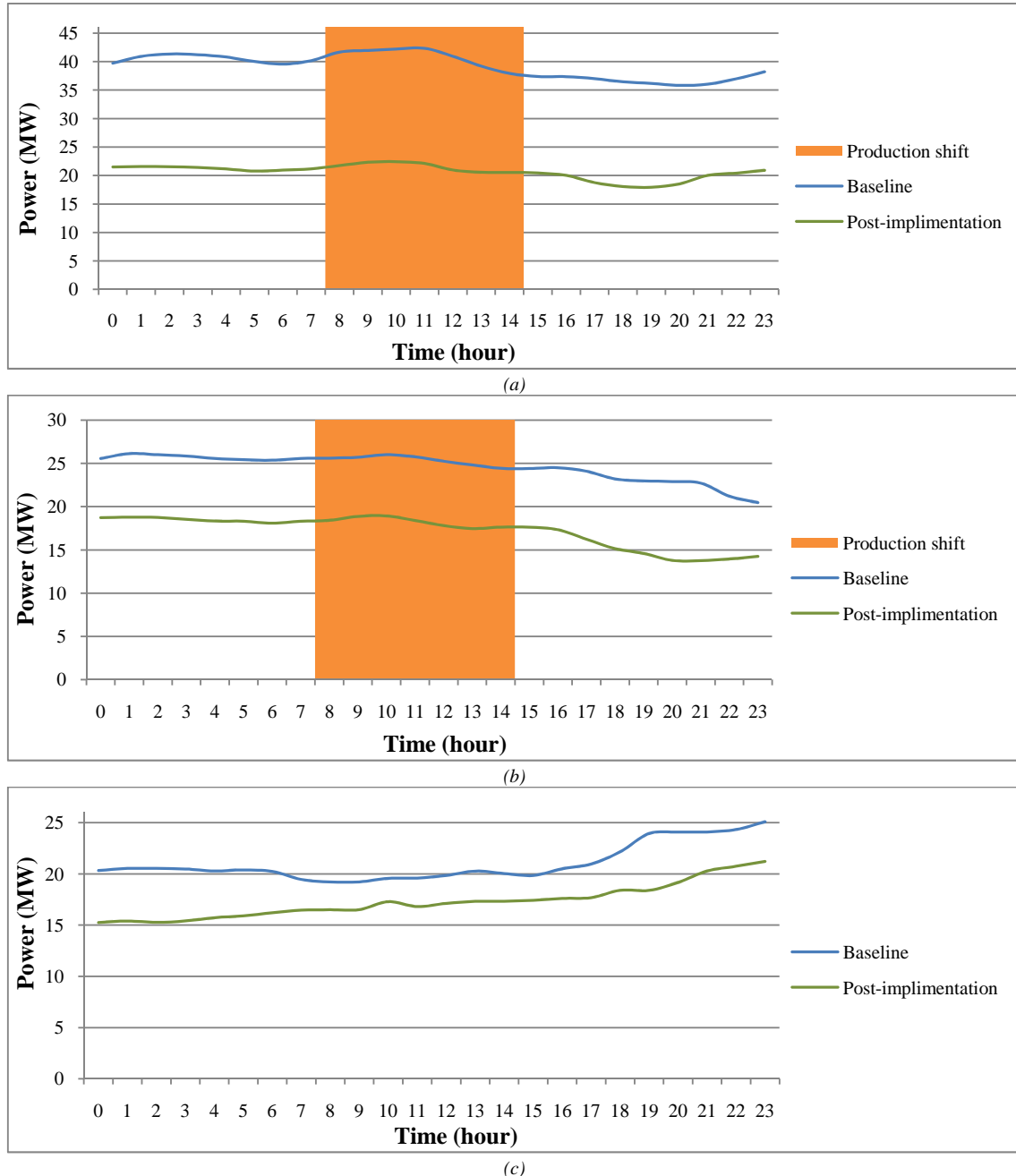


Figure 4-15: Impact on power consumption at Mine B for the average (a) weekday, (b) Saturday and (c) Sunday

The greatest improvement in efficiency was obtained for the average weekday shown in Figure 4-15(a). A possible reason for this is that the higher system pressure on weekdays also resulted in an increase in energy wastage through air blown off into the atmosphere.

Measurement of impact

The average electricity consumption and cost for an average weekday is calculated in Table 4-4.

Table 4-4: Average weekday power and electricity cost reduction at Mine B

Hour	Baseline (kW)	Actual (kW)	Impact (kW)	Summer		Winter	
				Cost per kWh (c/kWh)	Impact (R)	Cost per kWh (c/kWh)	Impact (R)
0	39,711	21,505	18,206	15.72	2,862	18.25	3,323
1	40,918	21,572	19,346	15.72	3,041	18.25	3,531
2	41,343	21,549	19,794	15.72	3,112	18.25	3,612
3	41,212	21,427	19,785	15.72	3,110	18.25	3,611
4	40,807	21,147	19,661	15.72	3,091	18.25	3,588
5	40,019	20,771	19,247	15.72	3,026	18.25	3,513
6	39,566	20,938	18,628	22.48	4,188	34.17	6,365
7	40,164	21,161	19,003	36.70	6,974	131.43	24,976
8	41,670	21,742	19,928	36.70	7,314	131.43	26,191
9	41,954	22,317	19,637	36.70	7,207	131.43	25,808
10	42,191	22,427	19,764	22.48	4,443	34.17	6,753
11	42,324	22,109	20,215	22.48	4,544	34.17	6,907
12	40,935	20,964	19,971	22.48	4,490	34.17	6,824
13	39,214	20,552	18,662	22.48	4,195	34.17	6,377
14	37,946	20,537	17,409	22.48	3,914	34.17	5,949
15	37,398	20,427	16,971	22.48	3,815	34.17	5,799
16	37,371	20,012	17,359	22.48	3,902	34.17	5,931
17	37,021	18,735	18,287	22.48	4,111	34.17	6,249
18	36,465	18,052	18,413	36.70	6,758	131.43	24,200
19	36,192	17,909	18,283	36.70	6,710	131.43	24,029
20	35,833	18,516	17,316	22.48	3,893	34.17	5,917
21	36,065	20,012	16,053	22.48	3,609	34.17	5,485
22	36,997	20,420	16,577	15.72	2,606	18.25	3,025
23	38,221	20,907	17,313	15.72	2,722	18.25	3,160
Total	941.5 MWh	495.7 MWh	445.8 MWh		R 103,634		R 221,124

The same calculations are done for the average Saturday and Sunday power profiles and the results are interpolated to monthly averages. The results of these calculations are shown in Figure 4-7.

Table 4-5: Summary of impact at Mine B

Average	Baseline (MWh)	Impact (MWh)	Summer impact (R)	Winter impact (R)
Weekday	942	446	103,634	221,124
Saturday	590	178	31,455	40,733
Sunday	505	90	14,107	16,377
Monthly	25,093	10,878	2,462,188	5,093,168

Figure 4-16 shows a comparison of the summer and winter cost reduction for an average weekday, Saturday and Sunday.

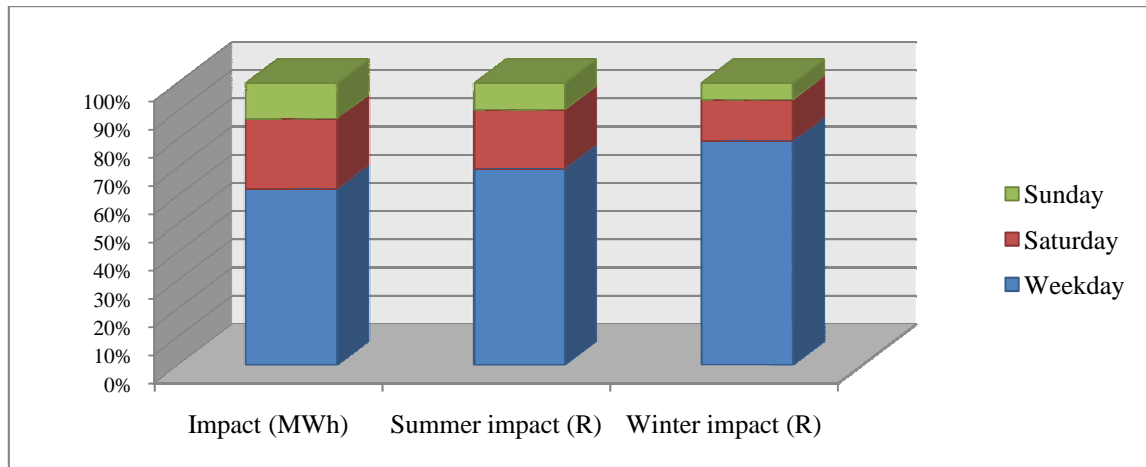


Figure 4-16: Comparison of impact on typical weekday, Saturday and Sunday at Mine B

The average weekday produced the largest electricity cost reduction with summer cost calculations. This reduction becomes substantially larger with the increased tariffs during winter months.

4.5 Implementation on other mine compressor systems

EMS was implemented at eight other mine compressor systems. The results obtained from these implementations are included in Appendix C and summarised in Table 4-6.

Table 4-6: Summary of average monthly results achieved on all implementations

Mine	System type	Assessment period (months)	Baseline	Impact			
			Consumption baseline (GWh)	Consumption reduction (GWh)	Consumption reduction (%)	Summer cost reduction (R)	Winter cost reduction (R)
A	Basic	9	5.59	1.64	29	351,131	676,651
B	Intricate	6	25.09	10.88	43	2,462,188	5,093,168
C	Basic	8	12.36	4.71	38	1,030,278	2,046,879
D	Basic	8	2.86	0.55	19	123,844	262,040
E	Intricate	7	21.86	3.94	18	835,407	1,580,645
F	Intricate	2	5.45	2.41	44	514,567	969,744
G	Basic	5	6.13	2.57	42	549,289	1,058,396
H	Intricate	3	29.31	13.65	47	2,997,038	4,838,049
I	Basic	7	11.33	4.44	39	946,471	1,811,915
J	Intricate	6	30.13	9.82	33	2,078,217	3,938,766
Average			15.01	5.46	35	1,188,843	2,227,625

The correlation between baseline electricity consumptions and achieved electricity reductions at all these mines are shown in Figure 4-17.

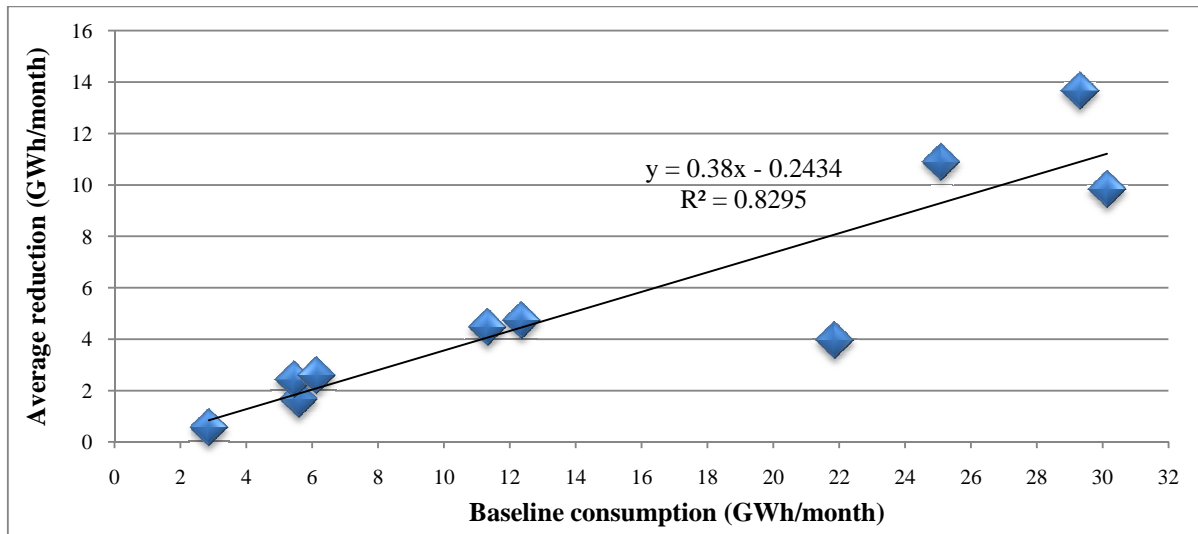


Figure 4-17: Baseline electricity consumption vs. achieved impact

A coefficient of determination (R^2) of 0.829 is obtained, which denotes a strong correlation between baseline electricity consumption and the achieved reduction. This graph shows that a compressed-air system with larger baseline consumption presents the opportunity for EMS to achieve greater reductions in electricity consumption.

The number of data points is insufficient to generalise this conclusion, but serve as a starting point for estimating the feasibility of future EMS implementations. The electricity reduction is estimated with the regression line equation ($y = 0.38x - 0.243$), which provides an indication of the possible monthly cost reduction. A projected payback period is obtained by comparing this cost reduction with the estimated initial cost of implementing EMS. This ultimately determines the feasibility of implementing EMS on a specific compressor system.

An average monthly reduction in electricity consumption of 35% (5.46 GWh) was obtained for the ten compressed-air systems on which EMS was implemented. In addition, this translates to an average monthly cost reduction of R 1,188,843.00 during a summer month and R 2,227,625.00 during a winter month.

4.6 Summary

EMS was implemented on ten compressor systems. Optimal compressor operation resulted in reduced electricity consumption of all these systems. The coefficient of determination (R^2), calculated for the baseline and reduction in electricity consumption, indicates a strong correlation between these variables.

The regression line equation, $y = 0.38x - 0.243$, can be used to calculate the projected reduction in electricity consumption based on the baseline consumption. This gives an indication of the expected electricity cost reductions, which provides an estimate of the feasibility of future EMS implementations.

An average monthly electricity reduction of 5.46 GWh was obtained by implementing EMS on ten mine compressed-air systems. The cost reduction increases significantly when higher winter tariffs are used to calculate the cost reduction. On average, a monthly electricity cost reduction of R 1,188,843.00 during a summer month and R 2,227,625.00 during a winter month was achieved. These results proved to be sustainable over the individual assessment periods, ranging from two to nine months.