Journal of Power, Energy, and Control

Research article

Implementation of Electrical Energy Efficiency and Reliability Optimization in Mining Company: A Case Study of Former Golden Star Wassa Limited, Ghana

Emmanuel Acquah

Electrical and Electronics Engineering Department, Faculty of Engineering, University of Mines and Technology, Tarkwa, Ghana

*Correspondence: acquahrenyto357@gmail.com

https://doi.org/10.62777/pec.v3i2.120

Received: 30 April 2026
Revised: 15 August 2026
Accepted: 4 September 2026
Published: 27 October 2026

Abstract: Mining operations constitute a significant part of operational expenditure, with electrical systems comprising 40-60 percent of total energy consumption in underground and surface mining operations. This paper is an evaluation of the execution of energy efficiency and reliability optimization strategies at Former Golden Star Wassa Limited, a gold mine in Wassa Akyempem, Ghana. An energy audit was carried out over six months that included the analysis of the power quality, load distribution, equipment efficiency, and the reliability of the systems in processing plants, hauling operations, and ventilation systems. The research utilized both qualitative measurements and quantitative performance measurements such as power factor correction, harmonic distortion measurement, and reliability measures such as System Average Interruption Duration Index (SAIDI) and System Average Interruption Frequency Index (SAIFI). It was found that strategic measures such as the installation of variable frequency drive (VFD) on the grinding mill, power factor correction to 0.95, LED lighting retrofit, and predictive maintenance measures decreased the specific energy consumption by 20.1 percent. Reliability of the power systems also improved, as the SAIDI reduced to 68 hours/year, and SAIFI to 14 interruptions/year. The financial analysis shows that the simple payback period is 2.3 years and an internal rate of return is 38, which indicates good economic viability. These results give evidence-based advice on how energy can be managed in mining activities, which are resource-intensive, and this adds towards sustainability in the extractive industry.

Keywords: energy efficiency, mining operations, power system reliability, variable frequency drives, power quality, Ghana, gold mining

Copyright: (c) 2026 by the authors. This work is licensed under a Creative Commons Attribution 4.0 International License.

1. Introduction

The world mining sector is under increasing pressure to lower their costs of operation and to minimize their impact on the environment, especially in terms of energy consumption and greenhouse gas emissions. Mining activities are energy-intensive, and electrical energy is one of the highest variable operating costs that can be controlled.

Energy expenses are as much as 15-30% of total operating expenses in sub-Saharan Africa, where mining is a major GDP contributor and source of employment, much more than the global average of 10 -15 percent [1]. This gap is brought about by the old infrastructure, ineffective machinery, and unreliable power supply systems that dog most of the developing economies.

These challenges are evident in the mining industry in Ghana, which has a contribution of about 5.8 percent to the national GDP and more than 37 percent of total export earnings [2]. The 5,000 MW of installed electricity generation capacity in the country is not able to keep pace with increasing demand, leading to periodic supply crunches that disproportionately impact the energy-intensive sectors [3]. Mining operations, due to their constant production needs and susceptibility to power outages, have a high economic cost of unplanned outages, which in large-scale mining operations is estimated between $50,000 and $200,000/hour, depending on the production level and the price of the mined commodity [4].

Former Golden Star Wassa Limited is a mining company with an underground and surface mining complex in Wassa Akyempem in the Western Region of Ghana with a production capacity of more than 200,000 ounces of gold per year. The process involves crushing and grinding circuits, flotation and carbon-in-leach (CIL) processing facilities, dewatering systems, ventilation systems, and materials-handling facilities. Before this work, the facility was consuming 181.4 GWh/year with an average energy consumption of 18.4 kWh per ton of ore processed, much higher than industry standards of 12-15 kWh/t of similar gold mining activities [5], [6]. In addition, the mine had a high number of power quality problems and an average of 28 supply interruptions per year, with an average of 5.1 hours per interruption, leading to losses of over 3,200 operating hours a year.

Energy optimization in the mining process is not only necessary in the short term to reduce costs. The mining industry around the world contributes about 11 percent to global energy use, and this figure is projected to rise to 13-15 percent by 2035 due to ore grade deterioration and the need to extract at deeper levels, which consumes more energy [7]. Mining energy use is a major cause of climate change due to carbon emissions, which account for about 4-7 percent of all greenhouse gases in the world [8]. The Ghanaian pledge, as stipulated in the Paris Agreement, that it will cut greenhouse gas emissions by 45 percent by the year 2030 compared to a business-as-usual situation puts extra strain on other key industrial consumers to cut down on energy consumption [9].

However, despite these calls, there is little effort to systematically apply energy saving efforts to the mining activities in Africa. The obstacles comprise capital limitations, lack of technical skills, lack of regulatory requirements, and organizational cultures that focus on the production volume, rather than energy output [10]. Although there are various research works that have analyzed energy efficiency in mining, based on theory or simulation, there are still limited empirical case studies recorded in the literature that show the actual results of implementation, especially in the developing country contexts.

This paper fills this gap by recording in writing the elaborate adoption of energy efficiency and reliability maximization strategies at Former Golden Star Wassa Limited. The objectives of the study are threefold: the study will offer a detailed baseline analysis of the energy consumption patterns and power systems reliability; the following step will offer the interventions of definite efficiency in large power-consuming systems; the third step will offer the evaluation of technical, economic, and operational consequences of the interventions. The analysis gives empirical evidence on the effectiveness of some technologies and management techniques in a realistic mining environment, and it has

practical implications for other mining endeavors in sub-Saharan Africa and other developing nations.

Mining has many energy efficiency dimensions. At the equipment level, it is concerned with making sure that individual machines such as crushers, grinding mills, pumps, and compressors are working at optimum. The process level entails researching the material flow, the comminution policy, and production planning so as to minimize unnecessary power use. At the system level, it comprises quality management of the power and optimization of the load factors and integration of renewable sources of energy where feasible. The reliability optimization is concerned with the frequency and duration of power outages that not only result in direct loss of production, but also cause wear and tear of equipment due to the start-stop and voltage transient cycles.

Wasa mining initiative is particularly a suitable case study due to the scale of the project, diverse electrical loads, and the urge to bring about general efficiency. The facility's electrical makeup includes an incoming supply of 34.5 kV dropped to 11 kV to be distributed to the major substations, and the further drop to 6.6 kV, 3.3 kV, and 415 V that is applied in various areas of the process. Massive loads include semi-autogenous grinding (SAG) mills, semi-autogenous 4.5 MW ball mills (3.2 MW each), crusher motors (800 kW maximum), flotation blowers (600 kW), mine dewatering pumps (1.8 MW), and underground ventilation fans (2.4 MW maximum load). This load diversity presents the opportunity to evaluate efficiency parameters of different applications and power ratings.

The method of implementation used in this study was a combination of technical interventions and organizational capacity building. Technical interventions involved installation of variable frequency drives on large rotating equipment, capacitor banks with power factor correction, high-efficiency motors to replace old ones, LED light retrofit, and installation of an energy management system with real-time monitoring. Some of the organizational actions included employee education on energy-related operations, setting of energy performance indicators, incorporation of energy measures into production planning, and the creation of predictive maintenance guidelines that focus on energy-intensive equipment. This total system approach acknowledges that sustainable energy efficiency entails both technological upgrades and cultural change in the organization.

2. Literature Review

Researchers and industry practitioners have become more concerned with energy efficiency in mining due to the growing energy cost and environmental regulation. Three main themes can be used to structure the literature: quantitative evaluation of the energy consumption of mining processes, the technological interventions aimed at efficiency improvement, and the reliability of the power system in industry.

2.1. Energy Consumption Characterization in Mining

Mining activities have very dynamic energy usage patterns that vary with the characteristics of the ore, mode of mining, processing needs, and the scale of mining. In [4], the author performed a life-cycle evaluation of energy in metalliferous mining and discovered that comminution processes, including crushing and grinding, constitute 30-50 percent of the total energy used by the mine site, with lower-grade ores needing more energy per ton of recovered metal. This observation has been supported by other research in different mineral types and geographic settings [11].

Gold mining in particular poses a special energy problem because of the generally low grades of ore (usually 1-5 grams per tonne), which requires processing of large quantities of material. In [6], the authors examined the energy consumption at fifteen gold mines in West Africa, with specific energy consumption of 11.2 to 24.7 kWh/t, with a median of 16.3 kWh/t. The large variation was due to the differences in the hardness of ore, the extent of liberation needed, and the efficiency of the installed equipment. Interestingly, the researchers found that the systematic energy management program in the mines led to a 15-25 percent decrease in energy use in the mines, compared with other similar operations that had no such program, thus highlighting the value of management commitment and technological efficiency.

A Ghanaian author in [5] studied energy consumption at five large gold mines, where grinding circuits accounted for the majority of the energy consumption (35-42 percent of total electrical consumption) and materials handling (18-24 percent), ventilation and dewatering (15-22 percent), and ancillary processes. The research defined benchmark levels of energy intensity and pinpointed certain inefficiencies such as oversized motors with low load factors, the lack of variable speed on applications with variable load profiles, and poor power factor with averaging values of 0.72-0.81 at surveyed locations.

2.2. Technological Interventions for Energy Efficiency

Variable frequency drives (VFDs) are among the best energy-efficient technologies to use in mining processes that require the use of pumps, fans, and conveyors whose flow needs differ. The affinity laws of centrifugal equipment suggest that the amount of power consumed by centrifugal equipment is proportional to the cube of the speed, i.e., a 20% decrease in speed would result in a 50% decrease in power consumption [12]. Several studies have recorded VFD applications in the mining industry where there was a 25-45%, 30-50%, and 15-30% energy saving on ventilation systems, dewatering pumps, and slurry pumps, respectively [13], [14], [15].

Nonetheless, VFD implementation in a mining setting is problematic and not always sufficiently covered in the literature. The severe conditions under which the equipment is operated, such as dust, humidity, and vibrations, as well as extreme temperatures, may lower the lifespan and reliability of the equipment unless appropriate requirements are specified and maintained [16]. Also, VFD switching frequencies may cause harmonic distortion that may affect power quality and disrupt sensitive instrumentation unless special harmonic damping techniques, like active filters or isolation transformers, are used [17].

The power factor correction enhances the efficiency of the system by lowering the reactive power requirement, thus minimizing the transmission losses and enhancing the voltage stability. The author in [1] surveyed power factor improvement initiatives in twelve South African industrial plants (three mines) and found that, on average, power factor improved by 0.74 to 0.94 with an 8-14 percentage point decrease in distribution losses. The economic value goes beyond the saving of energy to the prevention of utility penalty fees on the poor power factor and higher capacity on the existing distribution structures. In Ghana alone, the Electricity Company of Ghana (ECG) charges a monthly average power factor, which falls below a specified 0.85, up to 15 percent, which makes a high financial incentive for rectification measures [18].

The energy saving of high-efficiency motors is 28%-8% over standard efficiency motors of the same rating and higher percentages at partial load operation [19]. The incremental capital cost is usually 15-30 percent greater than typical motors, but the payback period in continuous-duty mining service is usually 1-3 years based upon

electricity tariff and hours of operation. Author in [10] assessed motor replacement programs in industrial plants in Korea, and established that systematic replacement of motors older than 15 years old or with less than 85% efficiency produced internal rates of return greater than 25% in most cases.

Retrofit of traditional lighting technologies (high-pressure sodium, metal halide, fluorescent) with LED-based solutions may save lighting energy by 50-75 percent of previous levels and enhance the quality of lighting and maintenance needs [20]. Other advantages of LED lighting are also seen in underground mining conditions, such as lower heat production (when ventilation loading is important), better low-temperature starting, and performance under vibration than conventional sources. Implementations of LED retrofit in coal mines in China have been reported with 60-68 percent energy reductions and payback periods of 1.8-2.4 years.

EMS is the combination of real-time monitoring, data analytics, and decision support tools to ensure the optimization of energy usage continues. The present-day EMS systems use machine learning algorithms to detect inefficiencies, forecast equipment failures, and suggest operational changes [21]. In [22], the author reported on EMS implementation in a copper mine in Zambia, showing an 11 percent decrease in specific energy consumption by better load scheduling, detection of unusual consumption patterns, and optimization of process parameters. Nevertheless, the success of EMS is highly reliant on the quality of data, interaction with users, and integration with the current operational systems, which in turn may pose a serious challenge in the operations of brownfields with archaic infrastructure.

2.3. Power System Reliability in Industrial Operations

In the industrial setting, power system reliability is usually measured with indices borrowed from utility distribution systems, the most common being the System Average Interruption Duration Index (SAIDI) and System Average Interruption Frequency Index (SAIFI). SAIDI is the total length of interruptions incurred by the average customer in a given time (usually one year), whereas SAIFI is the mean number of interruptions. In mining processes, where production continuity is important, other indicators are Mean Time Between Failures (MTBF), Mean Time To Repair (MTTR), and availability measures of critical equipment [23].

Power system reliability improvement strategies in mining incorporate redundancy, preventive maintenance, predictive maintenance, power quality monitoring and mitigation, and on-site generation or storage of energy incorporation in its strategies. The author in [15] showed that systematic condition monitoring of transformers, switchgear, and protective devices cut down the number of unplanned outages by 35-50 percent by early detection of incipient failures. Although costly in capital and equipment, investment in redundant supply paths and critical equipment sparing may be economically justified in high-value processes with downtime costs more than 100,000/hour [24].

Nuisance tripping of protective devices and premature failure of sensitive electronic equipment can be caused by harmonic distortion, voltage sags, and transients related to the start of large motors and the operation of VFDs. The author in [17] investigated the problem of power quality in mineral processing plants and discovered that Total Harmonic Distortion (THD) often surpassed the recommended limits by IEEE 519 of 5% of voltage and 8% of current in systems with large loads of nonlinear devices. The use of harmonic filters, isolation transformers, and power factor correction, which are designed to work in harmonic-rich conditions, brought THD levels down to reasonable levels and enhanced stability in the overall system.

2.4. Research Gaps and Study Contribution

Although the literature reviewed shows considerable evidence on the knowledge of individual energy efficiency technologies and reliability enhancement strategies, there are still a number of gaps. To begin with, the majority of studies investigate the effectiveness of individual interventions and do not compare combined efficiency programs involving several technologies and management practices. Second, empirical studies on African mining operations are absent, with most of the literature on Australia, North America, and Europe, where the operating conditions are much different. Third, there are few studies that have had detailed economic analyses that include not only direct energy savings but indirect benefits such as lower maintenance costs, longer equipment life, and losses through production by enhanced reliability.

This paper addresses these gaps by reporting on the implementation and the outcomes of an integrated energy efficiency and reliability program at one of the large-scale gold mining operations in Ghana. The holistic approach that also involves modernization of equipment, improvement of power quality, and building of capacity within the organization provides knowledge of the interactions between different interventions and the incremental returns. This study uses the example of Africa to educate other parts of the developing world that must grapple with the same problems of aging infrastructure, inadequate capital, and technical capacity. Finally, the overall economic analysis with different streams of benefits will provide a sound investment decision model in these cases.

3. Methods

This paper adopted a mixed-method research design that involved quantitative measurements of energy use and power system performance as well as qualitative measurements of the operational practices and organizational culture. The study involved three stages: baseline assessment, implementation of the intervention, and post-implementation evaluation, between March 2023 and August 2024.

3.1. Study Site and System Description

Wassa Akyempem, Western Region, Ghana (around $5^{o}22'$ N, $1^{o}58'$ W) is the site of a mining complex that was formerly Golden Star Wassa Limited. The plant has underground mining that goes 850 meters deep, surface mining of low-grade stockpiles, and a processing plant that has a nominal capacity of 2.4 million tonnes per annum. The power supply is through a special-purpose 34.5 kV feeder of the national grid and is contracted at 28 MVA. There are five main substations (34.5/11 kV), seventeen distribution substations (11/6.6 kV and 11/3.3 kV), and many low-voltage distribution boards (415 V).

Major electrical loads are distributed across several operational areas: (1) comminution circuit including primary crusher (800 kW), SAG mill (4,500 kW), and three ball mills (3,200 kW each); (2) processing plant encompassing flotation blowers (600 kW), agitators, pumps, and ancillary equipment totaling approximately 4,800 kW; (3) materials handling systems including conveyors, hoists, and underground haulage (combined 3,200 kW); (4) mine dewatering pumps (1,800 kW installed capacity); (5) ventilation systems including surface and underground fans (2,400 kW); and (6) support services including workshops, laboratories, offices, and lighting (approximately 1,200 kW).

3.2. Baseline Energy Assessment

The baseline test was done over twelve weeks (March- May 2023) to record the normal operating patterns during dry and wet seasons. Energy data were gathered in several ways:

1. **Power Quality Monitoring**: Three-phase power quality meters (Fluke 435 Series II) were placed at the main 34.5 kV incomer and six strategic distribution substations. Some of the parameters measured at 10-minute intervals included voltage, current, power factor, active and reactive power, harmonic distortion (up to the 50^{th} harmonic), voltage unbalance, and transient events. The duration of logging was 14 days at each site to create representative profiles.
2. **Equipment-Level Metering**: Portable power loggers (Yokogawa CW240) were installed on 42 large loads that comprised about 75% of total facility consumption. A minimum of seven days of monitoring of each load with various shifts and production conditions was observed. Such variables as power consumption, power factor, voltage, current, operating hours, and the load profile characteristics were measured.
3. **Process Energy Correlation**: The facility supervisory control and data acquisition (SCADA) system data on production (tonnes processed), ore hardness (Bond Work Index), grind size (P80), recovery efficiency, and plant availability were gathered and correlated with the energy consumption to develop specific energy consumption (SEC) values and determine process-related efficiency opportunities.
4. **Infrared Thermography**: Thermal surveys were performed on all significant electrical distribution equipment to determine hot spots that could be a result of loose connections, overloaded components, or failed equipment that needed remedial work
5. **Load Flow Analysis**: ETAP software was used to create a detailed electrical model of the facility distribution system. The model has been verified with measured data and applied to simulate different operating conditions, measure voltage drop, find distribution losses, and measure power factor correction measures.

3.3. Reliability Data Collection

The historical reliability data were taken from the maintenance management systems (SAP PM module) in the 24-month period before the study (January 2021-December 2022). Data included:

- Interruption events: date, time, duration, affected areas, classification of cause.
- Equipment failures: failed component, failure mode, repair time, impact on production
- Planned maintenance downtimes: frequency, time, prior notice.
- Power quality events: voltage sags, swells, harmonics, frequency variations.

These data were calculated as baseline values of SAIDI, SAIFI, MTBF, MTTR, and equipment availability. To determine the economic effects of unreliability, production loss reports were considered.

3.4. Intervention Design and Implementation

A detailed intervention program was developed based on the results of the baseline assessment and focused on the most effective opportunities. The implementation plan prioritized the interventions based on their potential to save energy, capital requirement, payback period, level of operational risk, and technological complexity. The most important interventions that are implemented are enumerated below:

1. **Variable Frequency Drives**: VFDs are installed on 10 of the largest motors, including two ball mills (3,200 kW each), 4 flotation blowers (600 kW each), and 4 large dewatering pumps (450 kW each). These drive selection criteria included overload capability, harmonic performance (18-pulse or active front end), ambient temperature rating, and redundancy features. Each installation had harmonic filters, input isolation, and connection with existing control systems. The commissioning involved determining the optimal speed control parameters and training operators on VFD usage.
2. **Power Factor Correction**: Four power factor correction (APFC) banks of 8.5 MVAR were located at four strategic points: main substation (4 MVAR), processing plant substation (2.5 MVAR), and two underground substations (1 MVAR each). Banks were designed using harmonic-rated capacitors and harmonized reactors to run safely in the harmonic environment generated by VFDs and other nonlinear loads. Control systems were coded such that they would maintain a power factor of 0.95 to 0.98 under different load conditions.
3. **High-Efficiency Motors**: Eighteen 75 kW to 800 kW motors were changed to IE3 efficiency class. Replacement criteria were motor age greater than 15 years old, efficiency less than 92% at rated load, or failure history, which showed that the motor was at the end of useful life. Every new motor was ordered with class F insulation, high-quality bearings, and the option of working with VFD where applicable.
4. **LED Lighting Retrofit**: A lighting retrofit plan was implemented in two stages where 1,240 high-pressure sodium (HPS) and metal halide lamps were phased out in underground workings, surface plant areas, and offices with LEDs. In harsh conditions with IP68 ingress protection, impact resistance (IK10), and explosion-proof certification, when needed, underground fixtures were specified. The retrofit involved redesigning the lighting layouts in order to optimize the lighting levels based on the task requirements as stipulated in South African mining standards.
5. **Energy Management System**: A complete EMS (Schneider Electric EcoStruxure platform) was installed that incorporated data from 68 metering points of all large loads and distribution substations. The system provides real-time visualization of energy being consumed, automated reporting of key performance indicators, variance analysis against targets, and alerts for abnormal consumption patterns. The existing SCADA system can be integrated with it, allowing energy data to be correlated with production parameters.
6. **Compressed Air System Optimization**: Control of air compressors was also updated to operate on variable speed with complex load-sharing algorithms instead of constant-speed operation. The survey was conducted on the leaks of the reticulation network by ultrasonic detection, and leaks were found to number 127, which were repaired. As the control system was adjusted to ensure that sufficient pressure was observed at all end-use points, pressure was lowered to 6.5 bar instead of 7.5 bar. Measurement of the compressed air system followed the same protocol used elsewhere in the study. Baseline air-system energy consumption was established from the equipment-level metering program: the compressor motors (combined installed capacity of approximately 950 kW) were among the 42 loads instrumented with Yokogawa CW240 loggers for a minimum seven-day period, cross-referenced against specific-power benchmarks (kW per 100 CFM delivered) taken from the compressor manufacturer's performance curves at the site's operating pressure. Post-intervention savings were quantified through the same metering points over an

eight-week window under comparable production conditions following commissioning of the variable-speed control retrofit and completion of the leak repairs. The contribution of the 127 individually repaired leaks was additionally estimated using standard orifice-flow calculations applied to the ultrasonic leak-survey data (leak diameter and count converted to an equivalent CFM loss, then to kW using the measured specific power of the system), which allowed the metered total to be cross-checked against an independent bottom-up estimate.

7. **Predictive Maintenance Program**: A proactive maintenance program was set up which focused on energy-critical equipment based on vibration analysis, oil analysis, thermography, and motor circuit analysis. All motors greater than 200 kW, all transformers, critical switchgear, and VFD systems are covered. Condition monitoring was used to optimize the maintenance schedules instead of time-based schedules.

Because several interventions were commissioned in sequence rather than simultaneously, the intervention-level savings reported in Table 3 were derived from a stepped, load-specific comparison rather than by decomposing a single facility-wide reduction after the fact. Each monitored load (see "Equipment-Level Metering") was assigned its own "before" window, taken immediately preceding that load's specific intervention, and its own production-normalized "after" window following commissioning. Where a load was affected by more than one intervention in close succession – for example, the ball mills received variable frequency drives before benefiting indirectly from the downstream power factor correction banks – the second intervention's savings were computed against the already-improved baseline for that load, not the original one, so that the same reduction was not credited to both interventions. This approach cannot fully isolate every interaction effect between interventions operating on the same electrical bus, which is one reason a portion of the total measured reduction could not be attributed to a single piece of equipment.

3.5. Post-Implementation Evaluation

After the implementation of every intervention (staged during 14 months between June 2023 and July 2024), performance was followed for at least eight weeks to determine the post-intervention measures of energy consumption and reliability. The evaluation involved the same measurement protocols that were used during the baseline assessment to make comparisons.

3.5.1. Performance Metrics and Analysis

Energy performance was quantified using the following metrics:

- **Specific Energy Consumption (SEC):** Total electrical energy consumed per ton of ore processed, calculated as:

$$SEC = \frac{E_{total}}{M_{ore}} \tag{1}$$

where E_{total} is the total electrical energy consumed (kWh), and M_{ore} is the tons of ore processed.

- **Load Factor:** Ratio of average demand to peak demand over a specified period:

$$LF = \frac{P_{avg}}{P_{peak}} \tag{2}$$

where P_{avg} is the average power demand, and P_{peak} is the peak power demand.

- **Power Factor:** Ratio of active power to apparent power:

$$PF = \frac{P}{S} = \frac{P}{\sqrt{P^2 + Q^2}} \quad (3)$$

where P is the active power (kW), Q is the reactive power (kVAR), and S is the apparent power (kVA).

Reliability was quantified using standard indices:

- **System Average Interruption Duration Index:**

$$SAIDI = \frac{\sum_i U_i N_i}{\sum_i N_i} \quad (4)$$

where U_i is the annual outage time for location i and N_i is the number of customers at location i.

- **System Average Interruption Frequency Index:**

$$SAIFI = \frac{\sum_i \lambda_i N_i}{\sum_i N_i} \quad (5)$$

where λ_i is the failure rate for location i.

- **Mean Time Between Failures:**

$$MTBF = \frac{T_{operating}}{N_{failures}} \quad (6)$$

where $T_{operating}$ is total operating time, and $N_{failures}$ is the number of failures.

Economic analysis was conducted using typical financial measures such as simple payback period, net present value (NPV), internal rate of return (IRR), and the levelized cost of energy saved (LCOES). It was analyzed using capital costs, operating cost savings (energy, maintenance, avoided production losses), equipment life, discount rate (12% real), and energy price escalation (6% per year on historical Ghanaian electricity tariff trends).

3.5.2. Data Quality and Validation

Several steps were taken to guarantee the quality and validity of data:

- All metering equipment was checked using calibration certificates.
- Where possible, duplicate measurements were made to determine outliers.
- The data on energy consumption was reconciled with utility billing.
- Cross-checking of production data and plant records, as well as metallurgical accounting, was done.
- Statistical process control charts: Abnormal values were detected by statistical process control charts to be investigated.
- Independent Measurements: An external consultant to verify selected measurements.

Standard error propagation techniques were used to determine uncertainty analysis, with a total uncertainty in SEC approximated as ±3.2% (95% confidence interval) when all uncertainties are added together, that is, energy measurement (±1.5) and mass of production (±2.8) uncertainty.

4. Results and Discussion

4.1. Baseline Energy Consumption and Power Quality

The initial analysis found a total electrical energy consumption of 181.4 GWh/year, with an average maximum demand of 22.8 MW and a load factor of 0.91. The data in Figure 1 indicate the distribution of energy consumption in key areas of operation.

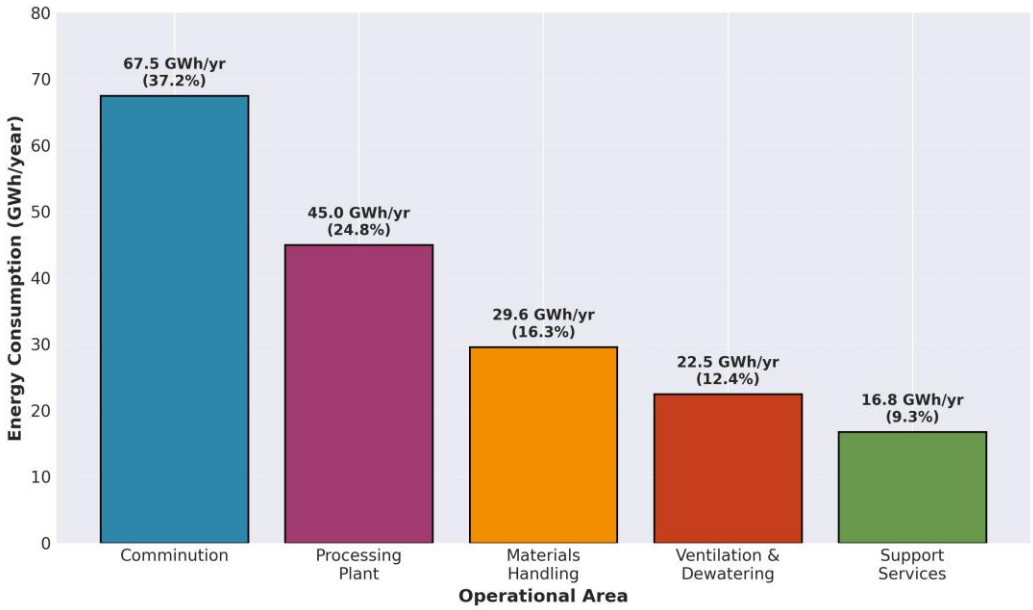


Figure 1. Baseline energy consumption distribution across areas of operation at Former Golden Star Wassa Limited.

Comminution operations incurred the highest percentage of 37.2 (67.5 GWh/year), as shown in Figure1; next were processing plant operations at 24.8 (45.0 GWh/year), material handling operations at 16.3 (29.6 GWh/year), ventilation and dewatering operations at 12.4 (22.5 GWh/year), and support services at 9.3 percent (16.9 GWh/year). This distribution is consistent with the results of similar gold mining activities in West Africa reported in [6], where comminution generally accounts for 35-42 percent of total consumption.

The baseline specific energy consumption was 18.4 kWh/t, obtained by dividing the total energy consumption of 181.4 GWh by the ore throughput of 9.86 million tons. This is higher than the industry standard of 12-15 kWh/t for comparable ore grades and grinding requirements [5], indicating a significant opportunity to improve efficiency.

The power quality analysis showed some worrying results. The facility-wide power factor was 0.78, which is significantly below the utility requirement of 0.90 and results in monthly penalty fees averaging GH 124,000 (about USD 10,300 at 2023 exchange rates). The main-incomer total harmonic distortion (THD) of the voltage and current was 6.8 percent and 12.4 percent, respectively, which are higher than the IEEE 519 limit. Significant 5^{th} (8.2%) and 7^{th} (6.1) harmonics were observed in individual harmonic components, which are indicative of six-pulse rectifier loads. Voltage unbalance averaged 1.8, within acceptable limits, but single-phase loads were unevenly distributed across individual feeders, resulting in unbalance up to 3.4%. Table 1 presents baseline performance data for the major motor applications, indicating inefficiency in the current equipment.

Table 1. Performance of key motor applications at baseline.

Application	Rating (kW)	Average Load (%)	Efficiency (%)	Power Factor	Annual Energy (MWh)
SAG Mill	4,500	82	94.2	0.87	28,460
Ball Mill 1	3,200	76	91.8	0.84	18,720
Ball Mill 2	3,200	74	91.6	0.83	18,240
Ball Mill 3	3,200	71	91.3	0.82	17,520
Flotation Blower 1	600	45	88.4	0.79	1,890
Flotation Blower 2	600	48	88.6	0.80	2,010
Dewatering Pump 1	450	52	89.2	0.78	1,740
Dewatering Pump 2	450	49	89.0	0.77	1,640
Primary Crusher	800	68	92.1	0.85	3,680

Table 1 shows that the majority of large motors were running at a much lower load than their rated capacity (average load 63%), suggesting either oversizing or operating conditions that are not in the design specification. The power factors of the ball mills were especially low (0.820.84) and added significantly to the total power requirement of the facility in the reactive mode. The efficiencies measured ranged from 88.4% to 94.2% with the older equipment (flotation blowers, dewatering pumps), showing significantly lower rates compared to the newer installations (SAG mill).

4.2. Baseline Reliability Performance

The review of 24 months of historical data (January 2021-December 2022) identified 56 interruption events with a total of 284 hours of lost production time. Table 2 summarizes baseline reliability.

Table 2. Power system reliability measures at the baseline (2021-2022).

Metric	Value	Unit
Number of interruptions	56	events
Total interruption duration	284	hours
SAIDI	142	hours/year
SAIFI	28	interruptions/year
Average interruption duration	5.07	hours/event
MTBF (critical feeders)	312	hours
MTTR	4.2	hours
Unplanned outage rate	73%	% of total

The SAIDI value of 142 hours/year is significantly higher than what is expected of industrial facilities in developed economies (1030 hours/year) but falls within the range of values that are reported for mining operations in sub-Saharan Africa. Notably, unplanned interruptions constituted 73 percent of the interruptions, which points to a high chance of improvement through predictive maintenance and equipment upgrades. Figure 2 was used to classify the causes of interruption into six categories.

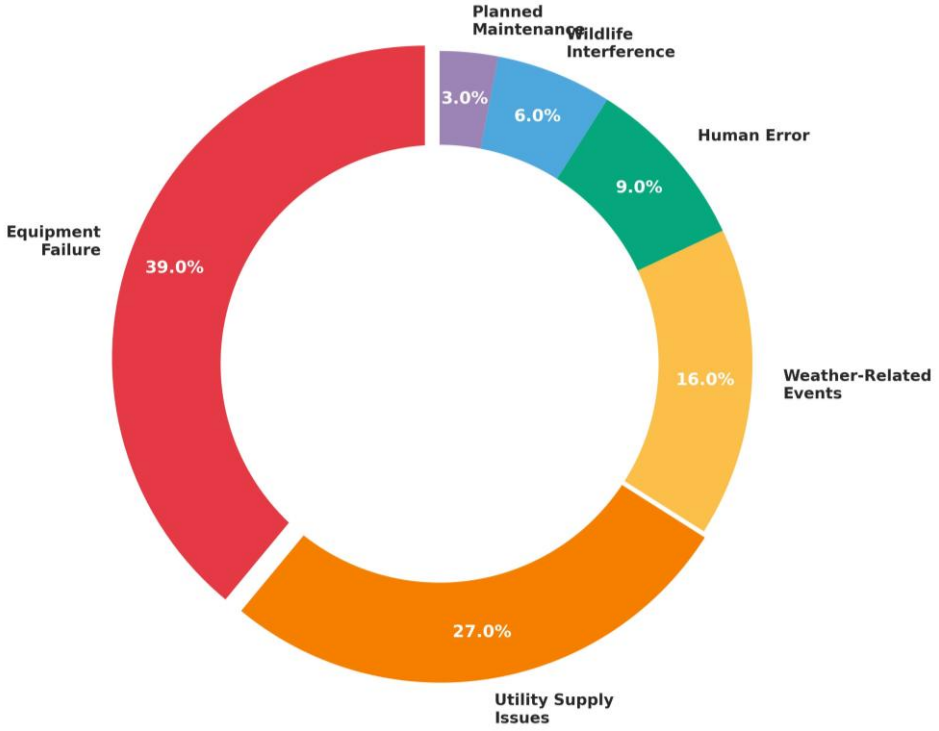


Figure 2. The classification of power interruptions during the baseline period (2021-2022).

Failure of equipment was the cause of 39% of interruptions (mostly transformer faults, breaker faults, and cable faults), utility supply problems 27, weather events 16, human error 9, wildlife interference 6, and planned maintenance 3. The large percentage of equipment breakdowns is indicative of the old infrastructure and lack of proactive maintenance, and the high utility charge is indicative of the difficulty of the Ghanaian electrical grid.

Economic consequences of reliability problems were enormous. With a conservative loss of production of 120,000 each hour (representing the price of gold, recovery rate, and direct operating cost), the 284 hours of lost time cost the company about 34 million dollars of lost revenue in the two years, or 17 million dollars per year.) This value does not include the damage to equipment caused by voltage transients, shorter equipment life due to the frequent start-stop cycles, and reprocessing expenses due to partially processed material that was stranded in the plant during the outage.

4.3. Post-Implementation Energy Performance

After the gradual introduction of efficiency measures from June 2023 to July 2024, all-encompassing energy monitoring was performed from August to December 2024. The total energy consumption dropped to 144.8 GWh (projected based on the monitored period), 36.6 GWh (20.2%) below baseline. Figure 3 looks at the comparison of the baseline and post-implementation energy consumption according to operational area.

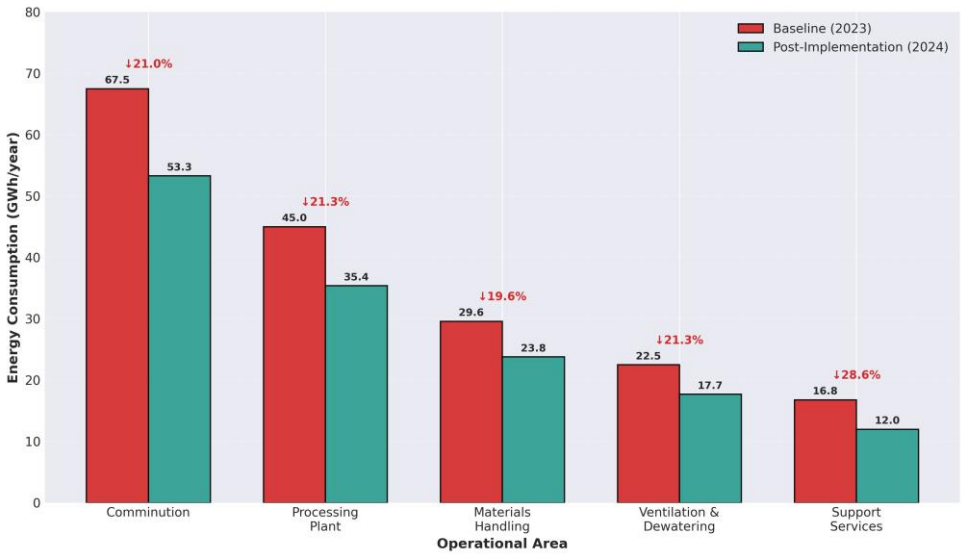


Figure 3. Comparison of energy consumption by operational area before and after efficiency interventions.

Figure 3 shows that all the areas of operation recorded considerable cuts. Comminution experienced the greatest change in absolute terms (14.2 GWh, 21% reduction) with the installation of VFDs on ball mills and replacement of motors. Processing operations used less energy (9.6 GWh, 21.3%) by implementing VFDs on flotation blowers and compressing air. Materials handling recorded a 5.8 GWh savings (19.6%) through conveyor motor replacement and operation improvement. In the installation of VFDs on fans and pumps, ventilation and dewatering saved 4.8 GWh of consumption. The greatest percentage change of -28.4 (4.8 GWh) was in support services as a result of extensive retrofits to LED lighting.

Specific energy consumption decreased by 20.1 percent, to 14.7 kWh/t, and moved the facility to an industry range of similar operations. This was despite the fact that the average ore grade (2.38 g/t to 2.32 g/t) slightly decreased over the time frame of the assessment, which would otherwise lead to higher specific energy consumption. The fact that the SEC decrease was successful despite the grade decrease depicts the real improvement in efficiency rather than the beneficial changes in the ore properties. Major interventions have detailed outcomes reported in Table 3.

Table 3. Energy savings from major efficiency interventions.

Intervention	Baseline (MWh/yr)	Post-Implementation (MWh/yr)	Reduction (%)	Savings (MWh/yr)
VFD on Ball Mills	54,480	43,150	20.8	11,330
VFD on Flotation Blowers	3,900	2,710	30.5	1,190
VFD on Dewatering Pumps	3,380	2,340	30.8	1,040
Power Factor Correction*	–	–	–	3,240
High-Efficiency Motors	8,720	8,190	6.1	530
LED Lighting Retrofit	6,840	2,180	68.1	4,660
Compressed Air Optimization	4,620	3,510	24.0	1,110
Total Measured Savings				**23,100**
Additional Operational Improvements**				13,500
Overall Total	**181,400**	**144,800**	**20.2**	**36,600**

*Avoided loss reduction, not direct consumption reduction

**Includes EMS-enabled optimization, maintenance improvements, operational adjustments

The baseline figures in Table 3 were listed against each named intervention refer only to the specific equipment targeted by that intervention (for example, the "VFD on Ball Mills" row reports the baseline consumption of the three ball mills alone), not to the facility-wide baseline; loads such as the primary crusher, materials-handling conveyors and hoists, non-VFD ventilation fans, and general facility base-load are captured in the Overall Total but do not appear as separate rows because they were not subject to a discrete, individually metered intervention. "Total Measured Savings" and "Additional Operational Improvements" are non-overlapping categories by construction – the former sums the itemised, individually metered interventions, while the latter comprises EMS-enabled optimisation and maintenance or operational adjustments at loads not individually re-metered post-intervention – and the two are additive without double-counting (23,100 + 13,500 = 36,600 MWh/yr, reconciling with the Overall Total reduction of 181,400 − 144,800 MWh/yr).

Table 3 demonstrates that VFD installations on ball mills produced the most significant individual savings of 11,330 MWh/year (20.8% savings), which is in line with theoretical expectations on the basis of affinity laws and experimental load profiles. Variable throughput rates of the ball mills are also dependent on the hardness of the ore and ideal grind size, thus forming perfect conditions for the application of VFD. The mills used to run at constant speed before VFD installation, and the feed rate was regulated through some other mechanisms, which led to some partial loading and energy waste.

The light retrofits had the greatest percentage reduction at 68.1 percent, outperforming the initial projections of 60 percent as more aggressive delamping (removal of unnecessary fixtures) and better light distribution led to less light needed. The 4,660 MWh/year absolute savings would translate to avoided electricity expenses of about 372, 000/a under average tariff rates.

Power factor correction resulted in savings of 3,240 MWh/year in distribution losses. Although direct current power reduction is not achieved by PFC, the enhancement of the power factor from 0.78 to 0.95 decreased the current flow in the distribution system. The loss reduction was determined using Equation 7 from measured resistance values of major cables and transformers.

$$\Delta P_{loss} = I^2 R \left(1 - \left(\frac{PF_{baseline}}{PF_{improved}} \right)^2 \right) \tag{7}$$

Furthermore, PFC removed monthly utility penalty fees of approximately GH 124,000 ($10,300), which would bring $123,600 savings each year in addition to energy savings.

The row "Additional Operational Improvements" in Table 3 (13,500 MWh/year) includes savings on EMS-enabled optimization, better maintenance practices, and the changes in operations that could not be directly attributed to a particular equipment improvement. After EMS installation, operators were provided with real-time feedback on energy consumption and the ability to change the operating parameters in order to reduce unnecessary energy consumption. Examples include optimizing the feed rate of grinding mills as a function of power consumption, instead of a fixed time schedule; adjusting the ventilation to actual occupancy and activity levels instead of operating the ventilation at maximum capacity; and detecting and fixing equipment failures as soon as possible by monitoring consumption anomalies.

4.4. Post-Implementation Power Quality Performance

In addition to the energy and reliability outcomes reported above, the retrofit program produced a substantial improvement in power quality at the main 34.5 kV incomer. Table 4 summarizes the baseline and post-implementation values for the key power-quality indices, referenced against the relevant IEEE 519 limits.

Table 4. Power quality performance, baseline versus post-implementation.

Parameter	Baseline	Post-Implementation	IEEE 519 Limit
Voltage THD	6.8%	3.2%	5.0%
Current THD	12.4%	5.8%	8.0%
5th harmonic (voltage)	8.2%	n/a – within composite THD	–
7th harmonic (voltage)	6.1%	n/a – within composite THD	–
Voltage unbalance (average)	1.8%	1.1%	–
Voltage unbalance (worst feeder)	3.4%	1.1%	–
Facility power factor	0.78	0.95	0.90 (utility requirement)

The reduction in both voltage and current THD to within IEEE 519 limits reflects the combined effect of the 18-pulse drive topology specified on the largest VFDs and the harmonic-rated capacitor banks and detuned reactors used in the power factor correction installation; these design choices were selected specifically to remain stable in the harmonic-rich environment created by the VFDs and other nonlinear loads, rather than being an incidental benefit of the retrofit.

Improvements in quality of power were also dramatic. The power factor of the facility was also boosted to 0.95 (0.95 to 0.98 is the target range), and penalty charges were removed, leading to voltage stability. Installation of harmonic filters with VFDs and 18-pulse drive topology (on largest units) resulted in a total harmonic distortion at the main incomer of 3.2% voltage and 5.8% current THD, well below the IEEE 519 limits. Voltage unbalance was reduced to an average of 1.1%, motor heating was minimized, and equipment life increased.

The profiles of the typical daily loads are compared between pre-implementation and post-implementation (Figure 4).

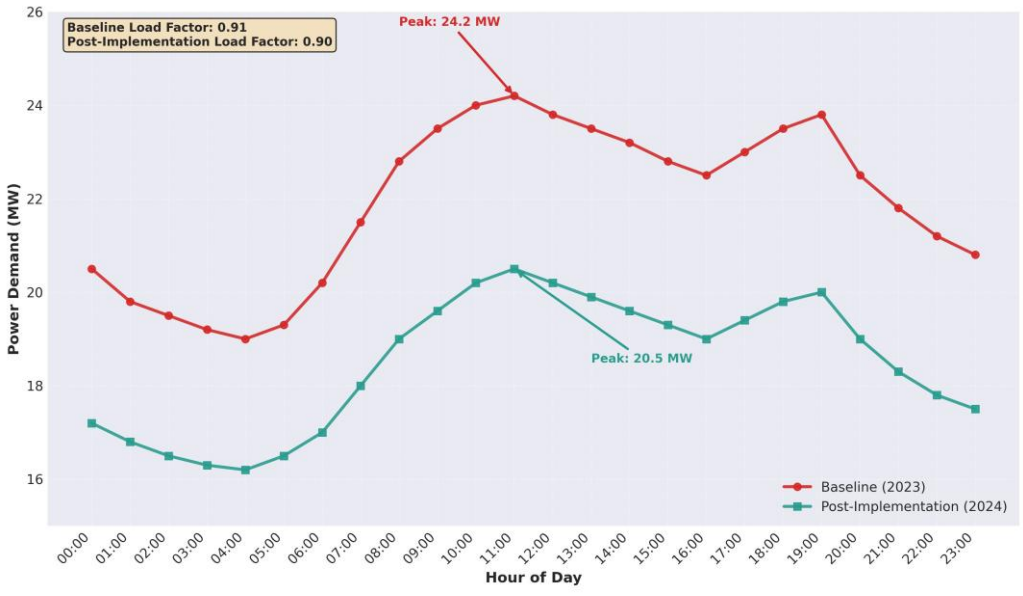


Figure 4. Comparison of the typical daily load profiles of the typical day prior to and after efficiency intervention.

As shown in Figure 4, the peak demand decreased by 24.2MW to 20.8MW (14 percent decrease), with an increase in the load factor to 0.94. Peak demand is reduced; hence, this gives extra capacity to the system that will be utilized in the future without the need to upgrade the distribution infrastructure. The enhanced load factor means that there is increasing uniformity of energy consumption during the day, which is important when both the facility is operating and when the grid is stable.

4.5. Post-Implementation Reliability Performance

Monitoring reliability between August 2024 and March 2025 (eight months) recorded 9 interruption events of 45 hours of downtime. An annual projection gives 13.5 interruptions and 67.5 hours of downtime. Table 5 gives a comparison between the baseline and post-implementation reliability.

Table 5. The reliability measures used compared to the results of interventions.

Metric	Baseline	Post-Implementation	Improvement (%)
SAIDI (hours/year)	142	68	52
SAIFI (events/year)	28	14	50
Avg. interruption duration (hours)	5.07	5.00	1.4
MTBF (hours)	312	628	101
MTTR (hours)	4.2	3.8	9.5
Unplanned outage rate* (%)	73	56	23

*Percentage point reduction, not percentage reduction

The 52% decrease in SAIDI and 50 percent decrease in SAIFI are considerable improvements in reliability. The increase in MTBF by twice the time (312 to 628 hours) represents the proper use of predictive maintenance to prevent failures by detecting and correcting incipient failures before they lead to unexpected outages. The small decrease in average interruption time (5.07 to 5.00 hours) indicates that when failures do happen, there is no significant difference in repair time, suggesting that future advancements should be directed towards decreasing response and repair time by increasing the availability of spare parts, diagnostic support, and training of technicians.

The decline in unplanned outages, now reduced to 56%, is a sign of progress toward proactive reliability management. But even unplanned outages are the prevailing majority, meaning that further progress can still be made by improving condition monitoring, being more aggressive in replacing equipment, and introducing redundancy in key circuits.

The monetary benefit of reliability gains is huge. A cut of 216 hours in downtime per year (284 hours to 68 hours) at 120,000 hours will save 25.9 million in annual losses. This value is considerably greater than the direct amounts saved in energy costs, which points out that reliability gains can often be worth investments without consideration of energy efficiency. The monthly trend of interruption frequency and duration during the study period is indicated in Figure 5.

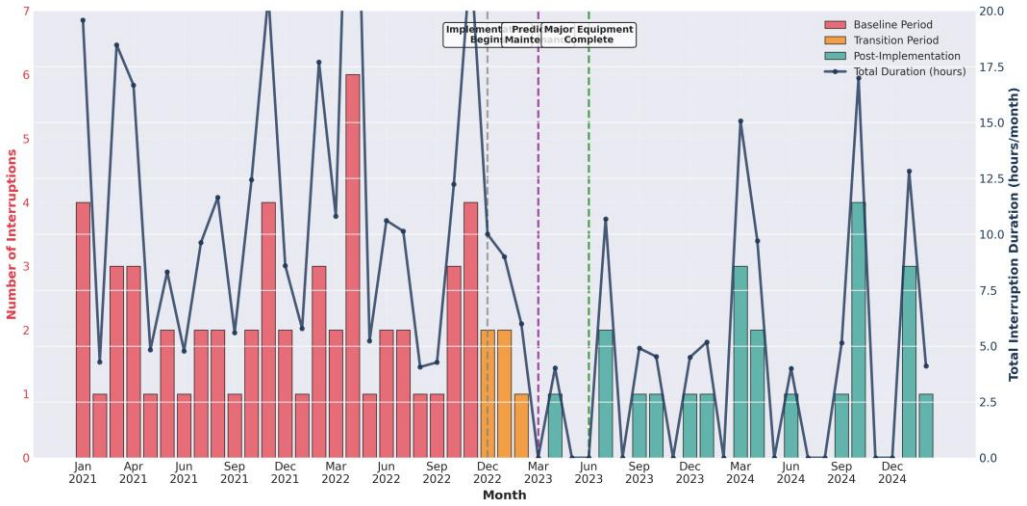


Figure 5. Trend of frequency and duration of power interruption per month, both during the implementation period and during the baseline period.

It is evidently improving after the introduction of predictive maintenance procedures (April 2024) and after completing significant equipment replacements (July 2024). The inconsistency in monthly values speaks to the stochasticity of equipment failures and the effects of seasonality (the highest rates of outage caused by the weather lead to the highest rates of equipment failures during rainy seasons, April-June and September-November in Ghana).

4.6. Economic Analysis

Table 6 summarizes the economic analysis for the overall program and major individual interventions.

Table 6. Economic analysis of efficiency and reliability interventions.

Intervention	Capital Cost (USD)	Energy Savings (USD/year)	PFC Penalty (USD/year)	Avoided Losses (USD/year)	Total Benefit (USD/year)	Payback Period (Years)	IRR (%)
VFD - Ball Mills	1,840,000	906,400	–	1,200,000	2,106,400	0.87	112
VFD - Flotation	340,000	95,200	–	180,000	275,200	1.24	78
VFD - Dewater	280,000	83,200	–	140,000	223,200	1.25	76
Power Factor Corr.	420,000	259,200	123,600	–	382,800	1.10	88
HE Motors	680,000	42,400	–	95,000	137,400	4.95	15
LED Lighting	1,220,000	372,800	–	–	372,800	3.27	27
Compressed Air	165,000	88,800	–	–	88,800	1.86	52
EMS	580,000	324,000*	–	520,000**	844,000	0.69	142
Reliability Improvement Program	385,000	–	–	18,600,000***	18,600,000	0.02	>200

*Direct EMS operational savings (includes portion of “Additional Operational Improvements”)

**Production losses avoided through early fault detection via EMS

***Production losses avoided through reduced unplanned outages

The reliability improvement program in Table 6 aggregates the avoided-downtime benefit of predictive maintenance together with the reliability gains attributable to VFD installation (reduced mechanical stress and start-stop cycling), motor replacement, and power-quality correction.

Assumes an electricity tariff of $0.08/kWh, production loss of $120,000/hour, 12% discount rate, and a 15-year equipment life. The overall initiative exhibits very high economic performance with a simple payback period of 2.3 years and an internal rate of return of 38, which is well above the average investment hurdle rates of mining projects

(15-20). The analysis takes conservative values such as an electricity tariff of 0.08/kWh (adjusted to 2024 Ghana industrial rates), a production loss value of 120,000/hour (calculated based on a 1,850/oz gold price, 92 percent recovery, and direct operating cost), a 12 percent (real) discount rate, and a 15-year equipment life.

Importantly, the economic argument is dominated by prevented production losses (25.9 million annually, 89% of energy benefits) as opposed to direct savings in energy (2.9 million annually, 10% of energy benefits). This conclusion highlights that the economic value of reliability can be much higher than the energy efficiency in the mining processes where downtime costs are high. Numerous energy efficiency investment choices in mining are all about savings in energy costs, and thus have a low overall value, especially when it comes to interventions that enhance efficiency as well as reliability, like VFDs, power factor correction, and predictive maintenance.

Similar results are observed with VFD installations on ball mills (payback of 0.87 years, IRR 112%) because of a combination of large energy savings (20.8 percent reduction on large loads) and reliability benefits (mechanical stress reduces equipment life, and maintenance costs are reduced). The three VFDs of 3,200 kW each, costing a capital of 1,840,000 ($191/kW), are a premium product with harmonic reduction and harsh-environment features suitable to the mining industry. Simpler drives may cost less (capital) by 30-40 percent but would most probably be less reliable and have poorer harmonic performance.

Replacements with high-efficiency motors are least attractive (payback 4.95 years, IRR 15%) because the benefits only represent small efficiency gains (2-6% depending on the motor rating and use) and a reduction in maintenance costs. The main reason why this intervention was undertaken was on motors at the end of useful life, where they needed to be replaced without any concern for efficiency. The added cost of high-efficiency compared to standard-efficiency replacement motors was between 15-25 percent, which is economically justified in continuous-duty mining service but might not be justified in low-duty cycle or high-start/stop service.

The EMS implementation has good economics (payback 0.69 years, IRR 142%), but attaching benefits to it needs interpretation. Direct operational savings of $324,000/year can be measured as the reductions in energy used for operations through optimization of grinding circuits, ventilation, and production scheduling enabled by EMS. Early fault identification and the ability to make timely corrective measures to prevent failures before they lead to unplanned outages (such as trending transformer oil temperature to detect cooling system degradation or monitoring motor current to identify bearing wear) saved the company an annual loss of production worth $520,000. These advantages, however, overlap with the predictive maintenance program to some extent, and a lot of care will be needed to ensure that they are not counted twice.

The sensitivity analysis (not represented in detail here because of lack of space) shows that the program economics are attractive over large ranges of key assumptions. The payback period will be between 2.8 and 1.9 years at a range of electricity prices between $0.05/kWh and $0.12/kWh (50 percent of base case). At a production loss of between 80,000/hour and 160,000/hour, the payback is between 3.1 and 1.8 years. The NPV at 8% to 16% discount rates is between 142 million and 78 million. The program breaks even in 5 years only in the extreme cases (electricity price of less than $0.04/kWh and production loss value of less than $60,000/hour).

4.7. Implementation Challenges and Lessons Learned

There were a number of key challenges in the implementation, which may be valuable to teach other similar projects:

- **Technical Complexity:** VFD installation into existing systems proved harder than anticipated, particularly when it comes to old equipment where much documentation is lacking. The ball mill VFDs required three more months of commissioning time than was originally scheduled due to some resonance issues and the need to rewrite control logic. The experience brings forth the importance of carrying out thorough pre-installation engineering studies and the supply of adequate commissioning time.
- **Production Disruption:** Due to unexpected maintenance, production had to be reduced in a number of installations even though the maintenance was not scheduled. The retrofit of the LED lighting in underground facilities necessitated provisional work stoppage in the areas, resulting in production costs incurred being cut down by approximately 2 percent of the six-month program implementation. The project economics and schedule should take this production effect into account.
- **Skills Development:** Maintenance technicians required considerable training so that they could properly utilize predictive maintenance equipment and their findings. The first reports of condition monitoring suggested that there were many visible anomalies; the majority of them were measurement artifacts or normal variations. Approximately nine months of concomitant operation was necessary to build trust in the technology and develop appropriate action thresholds, and to compare condition monitoring signals with the traditional fixed-interval inspections.
- **Organizational Change:** The shift in organizational culture towards a balanced production-and-efficiency, rather than production-first one was most likely among the largest obstacles. The first opposition to EMS-proposed modifications in operating parameters was by operators, who viewed energy efficiency as an abstract concept, which was not as important as maintaining operating habits as they were used to. To overcome this resistance, time was needed, and performance feedback was frequently provided, as well as energy measures were integrated into individual and team performance analysis and performance recognition programs to celebrate efficiency gains.
- **Supply Chain Constraints:** Some of its elements were characterized by long delivery times (4-8 months) due to unavailability within Ghana and regional supply chains. This experience has taught the importance of early procurement, strategic stocking of vital spares, as well as considering regional supply chain capabilities when selecting technology.

4.8. Broader Implications and Transferability

The case study of Former Golden Star Wassa Limited may provide several lessons to be used in the context of other mining operations, particularly in sub-Saharan Africa and other developing nations:

1. The dominance of avoided production losses in the economic case (89% of benefits) shows, in the first place, that the reliability gains must receive more attention in the mining energy efficiency programs. The conventional energy audit frequently targets kWh savings only, which may overlook the biggest value potentials. This paper has shown that combined programs that meet efficiency and reliability can attain high economic performance.
2. The difference in economics of the intervention (payback period 0.02-4.95 years) highlights the role of prioritization. There are always limited resources, and sequencing investments to generate quick wins (predictive maintenance, VFDs on variable loads) can be used to generate cash flow to support longer-payback interventions. This strategy was successful at Wassa, where VFDs and power factor

correction initially saved money, which was used in part to finance later LED retrofits and high-efficiency motor replacements.

3. The research supports the fact that the significant efficiency gains (20% decrease in SEC) can be attained in current operations without significant process transformations or manufacturing crises. The interventions were applied in the operating facilities in normal production and indicated that with brownfield retrofits, it was possible to obtain similar results as with the greenfield design optimization.
4. The issues faced, especially in skills building and organizational change, emphasize that technology is not enough. The enhancement of sustainability efficiency necessitates investment in human capacity, cultural change and management systems. The highly advanced equipment will not perform well when the operators do not understand its purpose, or the technicians are not able to maintain it.
5. The high economic performance (IRR 38%) of the Ghanaian environment with moderate prices of electricity (0.08/kWh) and standard mining economics implies that the same programs will be even more appealing in more expensive electricity environments. Electricity costs in most mining areas around the world are as high as $0.12-0.20/kWh, and this would shorten the payback period accordingly.

Local context is the determinant of the transferability of certain interventions. VFDs of changes in loads (pumps, fans, blowers) have a stable performance regardless of the context and should be prioritized interventions. The benefits of power factor correction are proportional to utility penalty structures or structures that are more aggressive in countries with aggressive penalties against poor power factor. LED retrofits can be used everywhere but with a different cost depending on the cost of electricity and the type of existing fixtures. Most appealing economics of high-efficiency motors occurs in continuous high-duty applications and is less attractive to intermittent or low-duty equipment.

4.9. Limitations and Future Research

There are a number of restrictions of this study. First, being a single case study, there is a limitation to the generalizability. Results may not be fully generalizable to other operations that have different ore characteristics (harder/softer, other mineralogy), processing routes (heap leaching vs. CIL, gravity separation) or size. Second, a post-implementation evaluation (8-12 months) may not have the capacity to capture long-term performance degeneration or performance variability across ore bodies and operating conditions. Third, assigning individual interventions to savings is associated with certain uncertainty because of the integrated implementation methodology-interactions between interventions (e.g., VFDs modifying power factor, interacting with PFC banks) then when combining effects might be overestimated or underestimated by a simple summation. Fourth, the economic analysis presupposes the future prices of electricity, the life and loss value of equipment that cannot be predicted in a mining situation. Fifth, the post-implementation reliability monitoring window (August 2024–March 2025) captures at most one of the two rainy seasons that dominate the baseline interruption record, so the pro-rata annualised SAIDI and SAIFI figures reported in this paper likely understate the true post-implementation annual values; a seasonally weighted recalculation is discussed in Post-Implementation Reliability Performance, and a full twelve-month monitoring cycle is needed to resolve this with confidence.

Research should be continued along several lines. First, there would be long-term performance monitoring (3-5 years) which would provide the information on sustainability of improvements and the rate of degradation. Second, controlled experiments might be preferable which involve manipulation of single settings (e.g., VFD

speed setpoints, grinding mill feed rates, ventilation schedules) to isolate causal relationships and optimum operating strategies better. Third, the generalizability would be strengthened with the extrapolation to other case sites of other mining techniques and mineral types. Fourth, the new opportunities of next-generation efficiency would be explored in the field of new technologies, such as the use of AI to optimize the process, the addition of renewable energy to battery storage in order to become grid-independent, and electrification of mobile equipment (haul trucks, loaders). Fifth, more precise understanding of combined effects might be obtained by modeling the interactions between the interventions in detail with the help of such methods as the factorial design or response surface methods.

5. Conclusions

This research paper has reported on the deployment and the results of an energy efficiency and reliability optimization program in Former Golden Star Wassa Limited gold mining operation in Ghana. The program delivered particular energy consumption savings of 18.4-14.7 kWh/t (20.1% reduction), power system reliability improvements with a decrease in SAIDI of 142-68 hours/year (52% reduction) and SAIFI of 28-14 interruptions/year (50% reduction), and good economic performance (simple payback period of 2.3 years The program involved variable frequency drive installation on large rotating equipment, power factor correction to 0.95, replacement of major motors with high efficiency motors, extensive LED lighting retrofit, optimization of a compressed air system, implementation of an energy management system and predictive maintenance procedures. Economic evaluation showed that avoided production losses due to reliability improvements (25.9 million annually) were more important than total benefits when compared to direct energy cost savings (2.9 million annually), which demonstrated the paramount value of considering reliability and efficiency in mining energy programs. Some of the implementation issues that occurred were technical complexity of VFD integration, production disruption requirement to make some installation, skills training requirement to develop maintenance staff, resistance to change in the organizational culture, and supply chain limitations of specialized equipment. These findings suggest that current mining process can be greatly enhanced in terms of energy efficiency and reliability through integrated programs, i.e., through combining the technologies upgrades with the organizational capacity building. The results can be easily generalized to other mining activities especially in sub-Saharan Africa but intervention choice must be localized based on the electricity prices, equipment baseline state, ore properties, and organizational potentials. This study to policy makers offers justification in the use of regulatory frameworks to encourage industry energy efficiency, utility tariff structures that punish bad power factor and encourage demand reduction and technical assistance programs that develop capacity in energy management. To industry practitioners, the findings provide a roadmap of how such programs can be put in place with clear prioritization direction, economic and practical findings based on challenges faced and hurdled during implementation.

Funding: This research received no external funding.

Data Availability Statement: The data used to support the findings of this study could be provided by the respective author on reasonable request with the understanding that there are confidentiality agreements with Former Golden Star Wassa Limited.

Acknowledgments: The author owes a huge debt of gratitude to the management and technical personnel of Former Golden Star Wassa Limited who cooperated and supported their participation in this study. It is with the help of the electrical maintenance team that a lot of credit is due to them during equipment installations and commissioning.

Conflicts of Interest: The authors declare no conflicts of interest.

References

[1] C. M. D. Majola and K. E. Langerman, "Energy efficiency in the South African mining sector: A case study at a coal mine in Mpumalanga," *J. South. Afr. Inst. Min. Metall.*, vol. 123, no. 9, pp. 451–462, Oct. 2023, doi: 10.17159/2411-9717/1788/2023.

[2] Ghana Chamber of Mines, "Performance of the Mining Industry in 2022," Accra, 2022. [Online]. Available: https://ghanachamberofmines.org/wp-content/uploads/2023/08/Performance-of-the-Mining-Industry-in-2023-.pdf

[3] Energy Commission Ghana, "2024 Energy Outlook for Ghana - Demand and Supply Outlook," Accra, 2024.

[4] T. Norgate and N. Haque, "Energy and greenhouse gas impacts of mining and mineral processing operations," *J. Clean. Prod.*, vol. 18, no. 3, pp. 266–274, Feb. 2010, doi: 10.1016/j.jclepro.2009.09.020.

[5] G. R. Ballantyne and M. S. Powell, "Benchmarking comminution energy consumption for the processing of copper and gold ores," *Miner. Eng.*, vol. 65, pp. 109–114, Oct. 2014, doi: 10.1016/j.mineng.2014.05.017.

[6] J. Jeswiet and A. Szekeres, "Energy Consumption in Mining Comminution," *Procedia CIRP*, vol. 48, pp. 140–145, 2016, doi: 10.1016/j.procir.2016.03.250.

[7] IEA, "Global Critical Minerals Outlook 2025," Paris, 2025. [Online]. Available: https://www.iea.org/reports/global-critical-minerals-outlook-2025

[8] M. Azadi, S. A. Northey, S. H. Ali, and M. Edraki, "Transparency on greenhouse gas emissions from mining to enable climate change mitigation," *Nat. Geosci.*, vol. 13, no. 2, pp. 100–104, Feb. 2020, doi: 10.1038/s41561-020-0531-3.

[9] S. T. and I. (MESTI) Ministry of Environment, "Ghana: Updated Nationally Determined Contribution under the Paris Agreement (2020 - 2030)," Accra, 2021. [Online]. Available: https://unfccc.int/sites/default/files/NDC/2022-06/Ghana%27s%20Updated%20Nationally%20Determined%20Contribution%20to%20the%20UNFCCC_2021.pdf

[10] J. Yang, "What does ETS do to real-side production activity? Firm-level evidence from Korea," *Energy Econ.*, vol. 161, p. 109528, Sep. 2026, doi: 10.1016/j.eneco.2026.109528.

[11] M. S. Powell and A. Bye, "Beyond mine-to-mill: Circuit design for energy efficient resource utilisation," in *Tenth Mill Operators' Conference*, Adelaide, SA: AusIMM, Oct. 2009, pp. 357–364.

[12] R. Saidur, S. Mekhilef, M. B. Ali, A. Safari, and H. A. Mohammed, "Applications of variable speed drive (VSD) in electrical motors energy savings," *Renewable and Sustainable Energy Reviews*, vol. 16, no. 1, pp. 543–550, Jan. 2012, doi: 10.1016/j.rser.2011.08.020.

[13] G. E. Du Plessis, L. Liebenberg, and E. H. Mathews, "The use of variable speed drives for cost-effective energy savings in South African mine cooling systems," *Appl. Energy*, vol. 111, pp. 16–27, Nov. 2013, doi: 10.1016/j.apenergy.2013.04.061.

[14] A. Chatterjee, L. Zhang, and X. Xia, "Optimization of mine ventilation fan speeds according to ventilation on demand and time of use tariff," *Appl. Energy*, vol. 146, pp. 65–73, May 2015, doi: 10.1016/j.apenergy.2015.01.134.

[15] J. Vosloo, L. Liebenberg, and D. Velleman, "Case study: Energy savings for a deep-mine water reticulation system," *Appl. Energy*, vol. 92, pp. 328–335, Apr. 2012, doi: 10.1016/j.apenergy.2011.10.024.

[16] A. Cooper, "ISO 50001— From Implementation to Integration ," *Strategic Planning for Energy and the Environment*, vol. 36, no. 2, pp. 69–79, 2023.

[17] J. Yaghoobi, A. Abdullah, D. Kumar, F. Zare, and H. Soltani, "Power Quality Issues of Distorted and Weak Distribution Networks in Mining Industry: A Review," *IEEE Access*, vol. 7, pp. 162500–162518, 2019, doi: 10.1109/ACCESS.2019.2950911.

[18] S. Lotsu, Y. Yoshida, K. Fukuda, and B. He, "Effectiveness of a Power Factor Correction Policy in Improving the Energy Efficiency of Large-Scale Electricity Users in Ghana," *Energies (Basel).*, vol. 12, no. 13, p. 2582, Jul. 2019, doi: 10.3390/en12132582.

[19] A. T. de Almeida, F. J. T. E. Ferreira, and G. Baoming, "Beyond Induction Motors—Technology Trends to Move Up Efficiency," *IEEE Trans. Ind. Appl.*, vol. 50, no. 3, pp. 2103–2114, May 2014, doi: 10.1109/TIA.2013.2288425.

[20] K. K. Sharma and D. P. Tripathy, "Design of illumination system in an opencast coal mine – a case study," *Journal of Mines, Metals and Fuels*, vol. 68, no. 11 & 12, pp. 362–371, 2021.

[21] K. Zhou, S. Yang, and Z. Shao, "Energy Internet: The business perspective," *Appl. Energy*, vol. 178, pp. 212–222, Sep. 2016, doi: 10.1016/j.apenergy.2016.06.052.

[22] CEEC: Coalition for Minerals Efficiency, "New Gold Inc. Global Energy Management implementation case study," 2014. [Online]. Available: https://www.ceecthefuture.org/wp-content/uploads/2014/12/GSEP_EMWG_New-Gold_case-study.pdf

[23] R. E. . Brown, *Electric power distribution reliability*, vol. 2nd. Boca Raton: CRC Press, 2009.

[24] Z. Li, M. Shahidehpour, F. Aminifar, A. Alabdulwahab, and Y. Al-Turki, "Networked Microgrids for Enhancing the Power System Resilience," *Proceedings of the IEEE*, vol. 105, no. 7, pp. 1289–1310, Jul. 2017, doi: 10.1109/JPROC.2017.2685558.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MSD Institute and/or the editor(s). MSD Institute and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.