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Energy Performance Assessment and Baseline Modelling for a Quarry in Gauteng Province, South Africa †

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Abstract

This paper presents an energy performance assessment and the development of an energy consumption baseline model for a quarry located in Gauteng Province, South Africa. Using 24 months of historical electricity consumption and production data, the energy use intensity (EUI) was calculated to benchmark the quarry against similar international operations. The results show that the quarry performs competitively, ranking third among seven comparable sites despite having no energy conservation measures (ECMs) in place. A linear regression model was developed to predict energy consumption based on tons produced, yielding a strong correlation (R^2 = 0.92) and statistically significant parameters. Model validation metrics—including a CVRMSE of 9%, Durbin–Watson value of 2.818, and negligible Net Determination Bias—indicate a reliable and accurate baseline suitable for future energy savings verification. The study highlights opportunities to further improve performance through energy management programmes and operational changes.

Keywords: baseline modelling; energy consumption; energy performance assessment; energy use intensity; quarry

1. Introduction

Current interest in achieving low carbon footprint to reduce the rapid occurrence of climate change is increasing globally [1–4]. Worldwide, it is estimated that buildings use over 40% of energy generated [5]. In emerging economies such as South Africa, China, and India, there is an expected growth in electricity demand for the year 2023 and beyond.

Electricity demand from China and India was predicted to increase by 5.3% in 2023 and 5.1% in 2024, with an average annual growth rate of 6.5%. In South Africa, the electricity demand was forecasted to increase between 2010 and 2018; however, this never materialized due to factors such as a drop in economic growth and implementation of energy efficiency and management systems by significant energy users as they tried to combat the rapid growth in electricity tariffs (i.e., 446% tariff growth between 2007 and 2009) [6,7]. Energy conservation measures (ECMs) are usually implemented to reduce the electricity demand of facilities, thus reducing their contribution to carbon footprint [5]. This includes implementation of energy efficiency systems and incorporating renewable energy in facilities [8,9].

It is thus vital to understand how much energy a facility is currently consuming (before ECMs are implemented) and how much it will consume or is consuming after ECMs are

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implemented. According to [5], energy consumption before the implementation of ECMs is referred to as the energy baseline, and it is used as a reference point with which to understand facilities' energy consumption trends. The energy baseline model can only be calculated through predictions based on energy-governing factors [5,10]. Figure 1 shows the graphical depiction of a baseline.

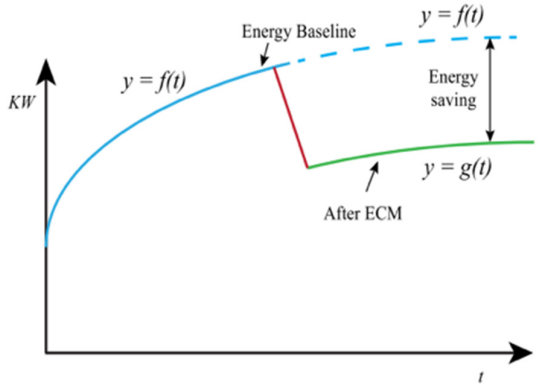


Figure 1. Depiction of a baseline according to the general concept of measurement and verification (M&V) [5].

Energy savings realized from implementation of ECMs, as depicted in Figure 1, are the difference between the energy baseline function (y = f(t), where y is the energy consumed at the given time t without ECMs (i.e., it is the predicted energy consumption)) and the after ECMs' implementation function (y = g(t)) in a period of time t. The formula below depicts the energy savings calculation:

$$\textbf{Energy savings} = \mathbf{f(t)} - \mathbf{g(t)} \quad (1)$$

When ECMs are implemented, f(t) does not exist and cannot be measured, but it can only be based on predictions [5].

The purpose of this paper is to assess the energy performance and model the energy consumption baseline model of a quarry located in the Gauteng Province, South Africa. The baseline model's performance is assessed to measure its accuracy and reliability.

2. Methodology

2.1. Site Description: Understanding the Quarry Process Flow and Electric Energy Use

To understand the process flow and energy users of the quarry, a site energy audit was conducted at the quarry located in the Gauteng Province, South Africa. The quarry produces different construction materials such as concrete stone, crusher sand, building sand, subbase material (G1–G8), and super sand. The crushing and screening plant layout is similar to the one shown in Figure 2.

Electrical energy is primarily used to operate motors for conveyors and feeders, the jaw crusher (primary crusher), screens, compressors, the cone crushers (secondary crusher and tertiary crusher), water pumps, and outdoor and indoor lighting.

The facility is supplied by Eskom, a state-owned utility, from a 11 kV overhead line into two 500 kVA, 11 kV/400 V transformers. There are two bulk smart electricity meters used to meter the entire facility, each covering the secondary side of each transformer. The total consumption of the facility billed by the utility (Eskom) is a combination of both meters.

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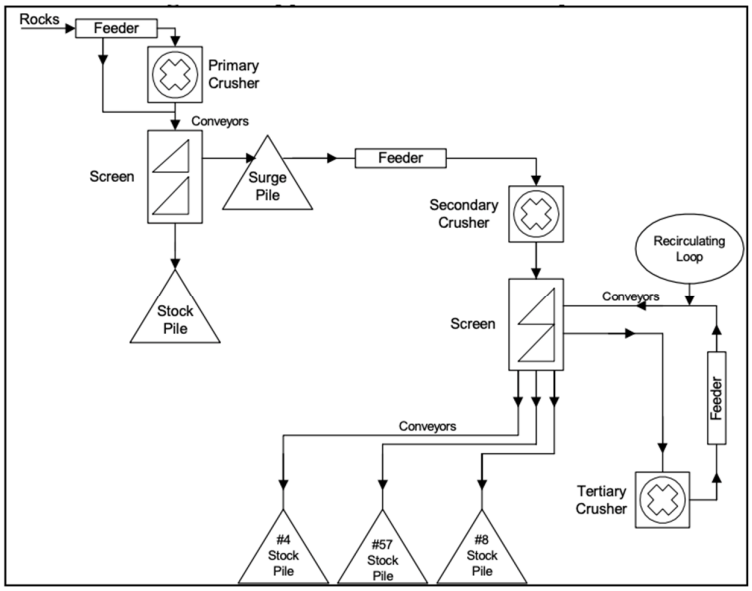


Figure 2. Screening and crushing plant layout [11].

2.2. Data Collection and Analysis

The aim of this paper is to assess energy performance and model an electric energy consumption baseline of the quarry using a data-driven method; thus, historical data is required. To assess the energy performance of the quarry, the energy use intensity (EUI) is used as per the formula below:

$$EUI = \frac{TEC}{SP} \quad (2)$$

where EUI is the energy use intensity (kWh/ton), TEC is the total energy consumption (kWh) and SP is the saleable product (ton).

Based on the formula above, it can be noted that TEC and SP are vital to assessing the energy performance of the quarry. Furthermore, according to the South African National Standard 50010:2018 (SANS 50010:2018), a baseline model should take into consideration measurement boundaries, measurement period, and an energy-governing factor [10]. The energy quantities should be determined by direct measurement of energy consumption through utility meters, appropriate calculations, or check meters. Furthermore, the baseline period must cover all operating modes of the facility [10].

The electricity consumption data was obtained from the utility for a period 24 months (June 2023 to May 2025), and the saleable product produced data was obtained from the quarry's production report for the same period. Based on this data, the EUI was calculated and is depicted in Table 1.

There was no missing data during the selected measurement period in Table 1. The energy consumption takes into consideration the total energy consumption of the facility and not the crushing and screening operations. This data must be processed to narrow it down to only include the energy consumption of the operations (screening and crushing).

This was performed using hourly meter data to analyze the operation dates, times, holidays, and shutdowns. Outliers were then identified using multiple methods such as the interquartile range (IQR) method and Z-score method. Unusual operation months (months without full production periods leading to too-high and too-low EUI) were also removed from the data set as part of processing as they do not represent the normal operation of the facility. All the removed months are highlighted below in Table 2.

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Table 1. Energy consumption, saleable product, and energy use intensity data.

Month-Year	Total (kWh)	Tons Produced (ton)	Energy Use Intensity (kWh/ton)
Jun-23	30,511	9578	3.19
Jul-23	27,679	16,856	1.64
Aug-23	31,832	15,916	2.00
Sep-23	20,325	10,253	1.98
Oct-23	34,518	11,060	3.12
Nov-23	26,748	6786	3.94
Dec-23	20,985	2034	10.32
Jan-24	24,606	6630	3.71
Feb-24	29,150	8862	3.29
Mar-24	30,832	10,640	2.90
Apr-24	28,325	14,076	2.01
May-24	26,317	9024	2.92
Jun-24	20,686	13,634	1.52
Jul-24	24,889	7683	3.24
Aug-24	28,157	5232	5.38
Sep-24	25,607	13,426	1.91
Oct-24	28,053	8367	3.35
Nov-24	27,610	16,170	1.71
Dec-24	19,836	5451	3.64
Jan-25	19,863	8457	2.35
Feb-25	16,250	10,526	1.54
Mar-25	24,231	10,830	2.24
Apr-25	28,553	11,520	2.48
May-25	27,863	14,065	1.98

Table 2. Energy consumption of operations, saleable product, and energy use intensity data post data processing.

Month	Total (kWh)	Tons Produced (ton)	Energy Use Intensity (kWh/ton)
Jun-23	18,105	9578	1.89
Jul-23	24,600	16,856	1.46
Aug-23	28,278	15,916	1.78
Sep-23	12,531	10,253	1.22
Oct-23	20,179	11,060	1.83
Nov-23	18,097	6786	2.67
Dec-23	4161	2034	2.05
Jan-24	17,291	6630	2.61
Feb-24	28,404	8862	3.21
Mar-24	22,466	10,640	2.11
Apr-24	23,773	14,076	1.69
May-24	23,858	9024	2.64
Jun-24	18,109	13,634	1.33
Jul-24	23,783	7683	3.10
Aug-24	26,562	5232	5.08
Sep-24	24,119	13,426	1.80
Oct-24	26,265	8367	3.14
Nov-24	25,555	16,170	1.58
Dec-24	3352	5451	0.62
Jan-25	14,608	8457	1.73
Feb-25	11,580	10,526	1.10
Mar-25	18,377	10,830	1.70
Apr-25	22,951	11,520	1.99
May-25	22,268	14,065	1.58

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The minimum, maximum, and average EUI having processed the data and omitted outliers are 1.46 kWh/ton, 2.05 kWh/ton and 1.76 kWh/ton, respectively.

Tables 3–5 show statistical values and an analysis of the relationship between the energy consumption and the tons produced within the processed data.

Table 3. Regression statistics.

Regression Statistics	
Multiple R	0.96100157
R Square	0.923524018
Adjusted R Square	0.91587642
Standard Error	1850.46863
Observations	12

Table 4. Analysis of variance (ANOVA).

	Regression	Residual	Total
df	1	10	11
SS	413,510,544.9	34,242,341.5	447,752,886.4
MS	413,510,544.9	3,424,234.15	
F	120.7600084		
Significance F	6.65345×10^{-7}		

Table 5. Modelled baseline equation parameters.

	Intercept	Tons Produced (ton)
Coefficients	2744.482573	1.486502398
Standard Error	1708.757687	0.135270796
t Stat	1.606127419	10.98908588
p-value	0.139326347	6.65345×10^{-7}
Lower 95%	−1062.866817	1.185100281
Upper 95%	6551.831964	1.787904516
Lower 95.0%	−1062.866817	1.185100281
Upper 95.0%	6551.831964	1.787904516

Based on the statistical values, there is a very strong correlation between the energy consumption of the operations and the tons produced. Furthermore, the Significance F and *p*-value are less than 0.05 (6.6534×10^{-7}, as shown in Table 4); thus, the correlation between the two is very significant, i.e., the independent variable reliably explains the variation in the dependent variable. Moreover, the Coefficient of Determination (R^2) is well above 90% as shown in Table 3, and this indicates that more than 90% of dependent variable (energy consumption) observed can be explained by the independent variable (tons produced).

2.3. Energy Performance Assessment and Benchmarking

The quarry has not yet implemented any ECMs, and there is no energy management programme in place. To assess whether the quarry is operating efficiently, a comparison with and benchmarking to other similar quarries were conducted using the energy use intensity. A study was conducted in the United States for similar operations, and that quarry had an EUI of 2.09 kWh/ton over a year [11]. This is higher than the average at the Gauteng quarry. Another quarry in Turkey had an average EUI of 2.72 kWh/ton over a year, which is higher than the Gauteng quarry's EUI. Figure 3 below depicts the EUI of other additional five pilot sites studied in [12].

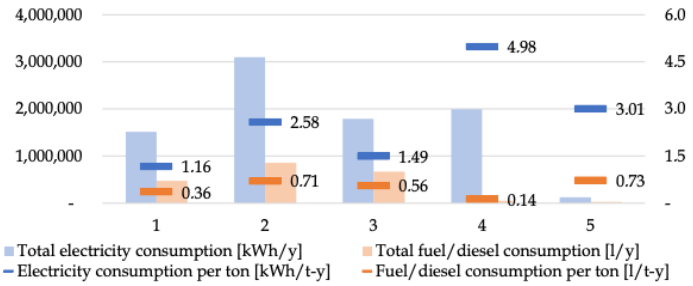


Figure 3. Electricity, fuel consumption, and energy use intensity (electricity) [12].

Based on the average EUI of seven quarries from the existing literature, the Gauteng quarry falls within the better-performing quarries when assessing energy performance. The Gauteng quarry is performing better than five quarries, and only two quarries as shown in Figure 3 are performing better than the Gauteng quarry.

2.4. Baseline Modelling and Baseline Model Performance Assessment

Based on the data available, the energy consumption baseline was modelled using linear regression as per Table 5. The modelled baseline equation is as follows:

$$PEC = 1.4865 \times (TP) + 2744.48 \quad (3)$$

where PEC is the predicted energy consumption (kWh), TP is the tons produced (Ton), 1.4865 is the gradient of the best fit regression line, and 2744.48 is the y-intercept of the same line, as shown in Table 5, row 1.

Table 6 depicts the predicted energy and the residual energy from the actual energy.

Table 6. Baseline model prediction.

Month	Total (kWh)	Tons Produced (ton)	Predicted kWh	Residual
Jun-23	18,105	9578	16,982	1122
Jul-23	24,600	16,856	27,801	−3201
Aug-23	28,278	15,916	26,404	1874
Oct-23	20,179	11,060	19,185	993
Dec-23	4161	2034	5768	−1607
Apr-24	23,773	14,076	23,669	105
Sep-24	24,119	13,426	22,702	1416
Nov-24	25,555	16,170	26,781	−1226
Jan-25	14,608	8457	15,316	−708
Mar-25	18,377	10,830	18,843	−466
Apr-25	22,951	11,520	19,869	3082
May-25	22,268	14,065	23,652	−1384

To measure the performance of the model, the following metrics in Table 7 were calculated as per [13].

Table 7. Baseline model performance metrics.

CVRMSE	9%
Durbin–Watson	2.818
NBE/NDB	1.39938×10^{-16}

According to [10,13], the coefficient of variation of the root mean squared error (CVRMSE) should be below 20% when the data used is less than 12 months in times-

pan. The model has a CVRMSE of 9%. Furthermore, the Durbin–Watson value for the model is 2.818, which according to [13] is acceptable. Lastly, the net determination bias (NDB) should be less than 0.005% according to the ASHRAE Guidelines for Measurement of Energy and Demand Savings. The model's NDB is well below this value. Based on this, the model seems to be a good fit and is a reliable model to use as a baseline.

3. Conclusions

Based on the energy performance assessment of the quarry, when using the EUI, the quarry can be ranked in third place as compared to the other seven quarries. This performance is not too bad provided that the quarry has not implemented any energy efficiency measures or ECMs since its establishment. There is a strong correlation between the energy consumption and the tons produced. The energy consumption is dependent on the tons produced.

Lastly, the modelled baseline performance was within acceptable ranges based on application of relevant standards and metrics for performance assessment. This model is therefore accurate and reliable and can be useful in predicting energy consumption post implementation of ECMs.

To improve the energy performance of the quarry, ECMs must be implemented together with the adoption of an energy management programme. Furthermore, a change management process must be applied to the operations of the plant to ensure that the plant is not operated under no load. This will reduce the energy use intensity and improve the energy performance of the quarry. Based on the high-level energy audit and analysis, energy savings of approximately 20–30% and monetary savings of approximately 39% can be realized. Furthermore, a 20 to 30% reduction in carbon can be realized.

In the future, more detailed energy audits can be conducted to ensure that all opportunities for energy savings are identified and analyzed for potential implementation.

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