A case study of an electrical efficiency audit in an industrial site

ABSTRACT

The mastery of energy consumption is a major concern to maintain planet habitable for future generations (climate change). An energy monitoring system is a powerful tool to reach that target and it can be used in all types of residential, commercial, and industrial buildings. This article relates its utilisation in an industrial site. Research has also been done on motors to reduce consumption of this high consuming equipment. This research has been launched by using an energy monitoring system. The savings identified are the following: Financial = \$60,336; Environmental = 70.6 CO2 tons (794,000 kWh of electricity, 8,7% of the site electrical consumption). The cost is \$128,680 and the Payback is 2.3 years.

Keywords

Monitoring, Metering, Targeting, Energy, Motors efficiency, VSD

INTRODUCTION

This paper is focused on energy efficiency through metering and monitoring that is the first step before launching actions to reduce green gas houses. Motors are among the major consumption equipment and therefore carbon emission. Motors and associated variable sped drive (VSD) have been selected for applying the strategy after metering and targeting.

Motors consume an estimated quarter of the electrical energy used by manufacturing sites **(Cengiz & Mamiş, 2015).** However, they are often overlooked and, as a result, many sites have relatively inefficient motor operations.

According **to Goman et al. (2019)**, electric motors consume 46% of the world’s electricity. They account for about 70% of the total industrial electricity consumption.

All details of the findings of the research are explained. The experimentation held in an industrial site in Belgium.

The site has an existing metering & monitoring system, which automatically collects energy data from a series of digital meters located around the facility. The system provides weekly reports on electricity and water consumption by transformer and building location. In addition, there are few analogue meters, which are manually read on a weekly or monthly basis and inputted into the system. The system is primarily utilized as an energy accounting tool to provide strategic energy consumption reports by location. The system is not currently used to provide real time energy monitoring and targeting.

This system is essential to conduct energy audit and for energy performance management **(Tallinia & Cedola, 2016; M’baye, 2022a; M’baye, 2022b).**

1. Method & Material

1.1. Metering, Monitoring and Targeting

Energy savings related to implementing a good monitoring & targeting system can yield significant savings **(Costa et al., 2013)**. According to **Lee & Cheng (2015)**, typical savings are between 14.07% and 16.66%. This information is obtained through several case studies on monitoring and targeting in industrial and tertiary buildings (commercial, administrative etc.).

A monitoring and targeting system must at least:

- Record energy consumption and any other factors that affect energy use (weather, occupancy, etc.).
- Compare the energy use to previous years, or to yardsticks representing typical or target energy performance.
- Alert sudden changes in energy use patterns.
- Provide regular summary reports.
- Provide the relevant cost centers with their individual energy costs.

It is judicious to compare energy meters data with other kind of data such as production or external temperatures (variable data). The following charts (figures 1, 2 and 3) illustrate how this analysis can be undertaken using a regression analysis.

As represented in figure 1, by plotting electricity versus production, a linear trend line (linear regression) can be drawn **(Ciulla & D'Amico, 2019; SEAI, 2019).** Equations in the following format is derived:

$$\mathbf{y = mx + c} \qquad (1)$$

- **y** being electricity consumption
- **x** being the production variable
- **m** being the gradient of the line
- **c** being the constant or base load that is consumed when there is no production.

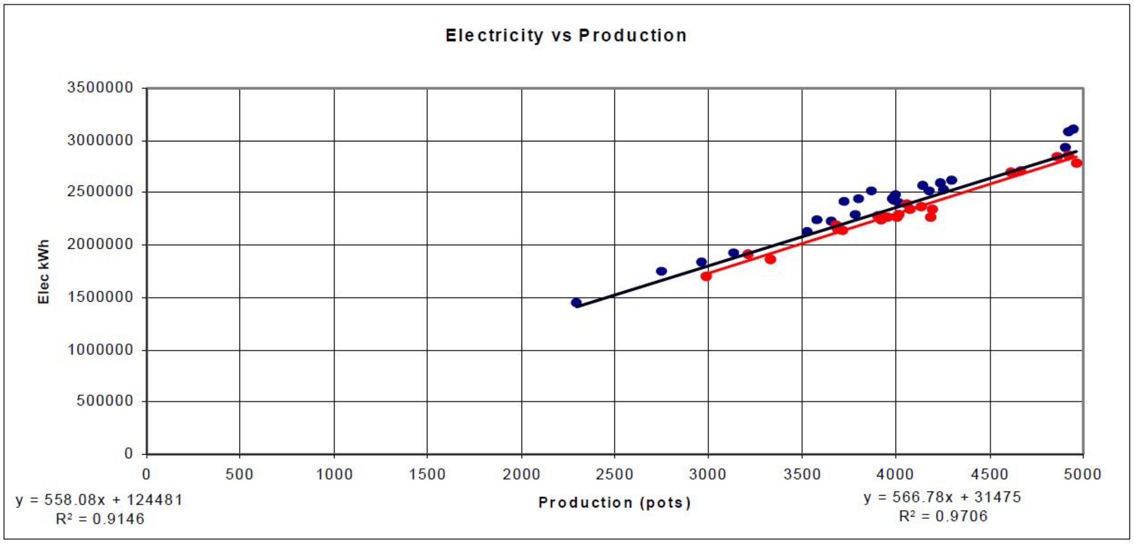

Figure 1: Example of linear regression analysis

The equation (1) becomes the target and can be further analyzed as a CUSUM (Cumulative Sum) graph as seen in figure 2 **(SEAI, 2019)**.

According to **Taner et al. (2018)**, CUSUM is a numerical calculation for energy consumption analysis that determines the annual energy efficiency for factories.

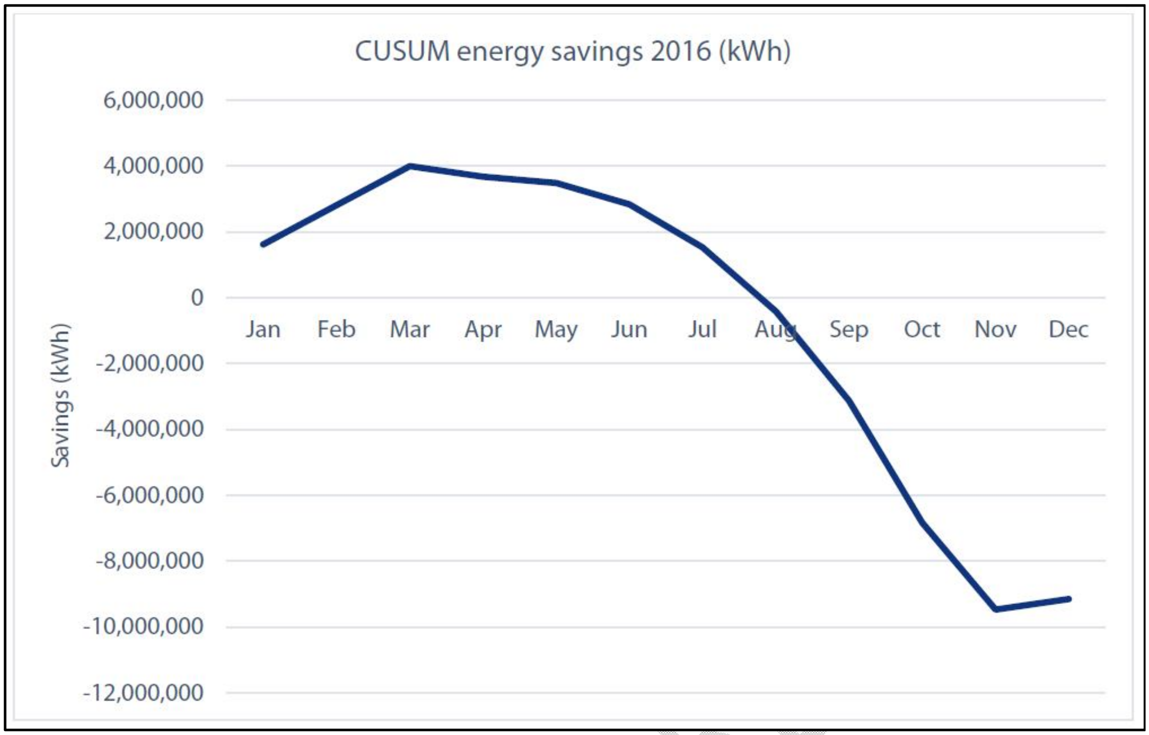

Figure 2: CUSUM electric arc furnace example (SEAI, 2019)

This analysis subtracts actual use from the predicted use (y=mx+c). The difference is then added together each time the analysis is undertaken. On target would be straight along the X axes, behind target would be below the axis and ahead of target would be above the target. Exception reports can then be created when the actual consumption deviates away from its target by an agreed tolerance **(Hilliard & Jamieson, 2013).**

Using the data gathered from the existing Environmental Monitoring System for the site, the analysis of the production and electricity consumption is shown in the figure 3.

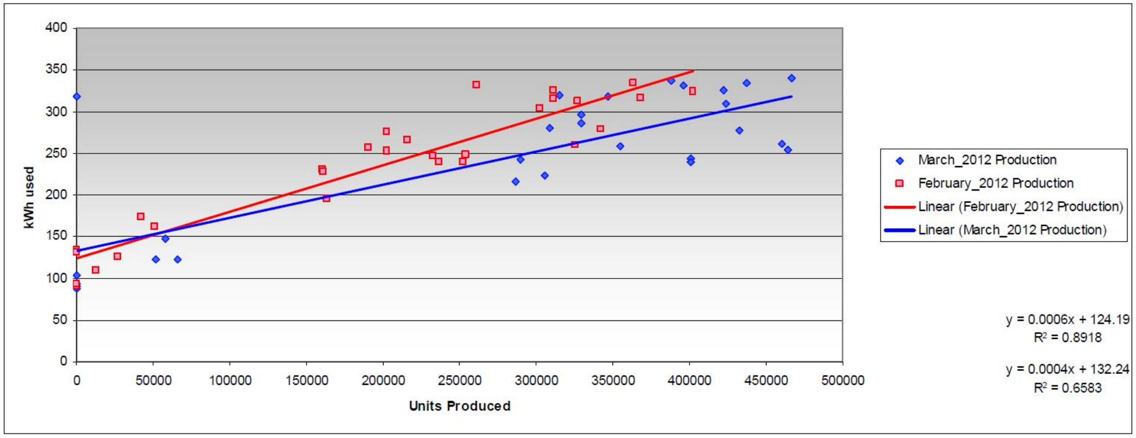

Figure 3: Electricity and production linear regression analysis for February and March 20212

The CUSUM analysis for the site energy usage compared to the production is represented in figure 4.

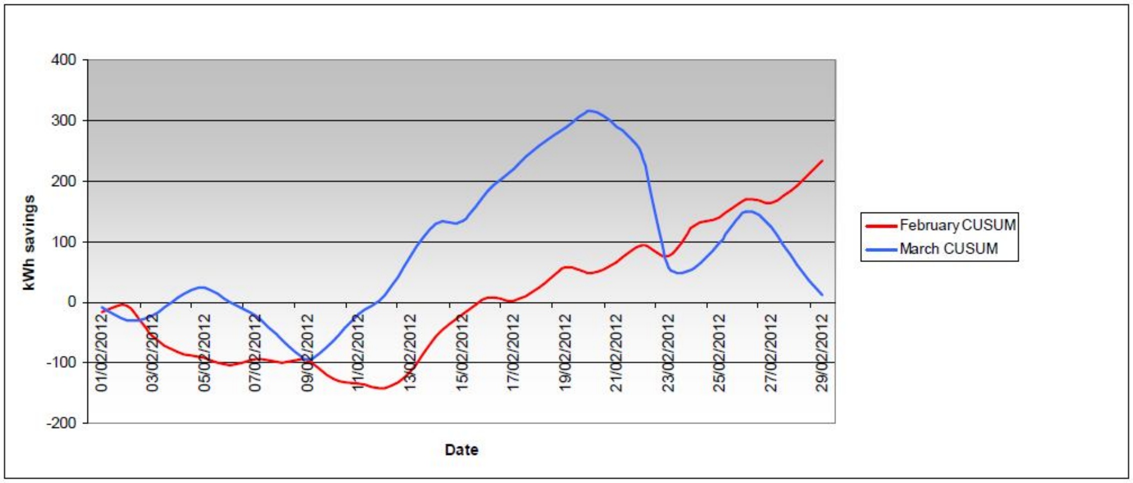

Figure 4: CUSUM analysis for the site energy usage compared to the production for February and March 20212

The above charts show that the site currently has a base load of circa 130 kWh when there is no production. The data gathered for the month of February had a higher level of accuracy than that collected in March, this demonstrates that the site energy load did vary relatively consistently with the production.

Analyzing the data for March, there is much more variation in the energy consumption relative to the production figures. The cause of this fluctuation is a change in weather (favorable impact) and 3 days of shutdown of the site during the month of March.

1.2. Motors

1.2.1. Motors - High Efficiency definition

Van Rhyn & Pretorius (2015) state that the International Electrotechnical Commission (IEC) has published an international standard that lately defines 5 distinct energy efficiency classes for three phase motors: IE1, IE2, IE3, IE4 and IE5. The IE classes replace the previous CEMEP EFF classes.

The figure 4 contains the efficiency of each class following motor rated power.

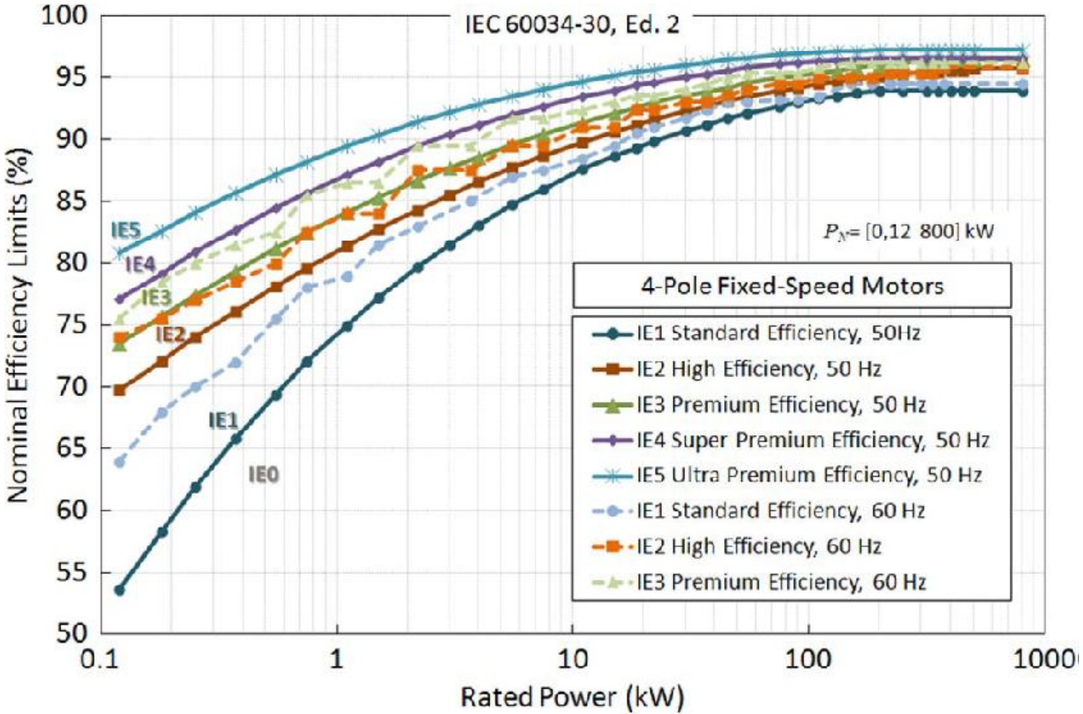

Figure 5: IEC 60034-30 nominal efficiency class limits, for four-pole motors (De Almeida et al., 2019)

There is another standard for high efficiency motors - WIMES (Water Industry Motor Efficiency Standards). This standard defines minimum high efficiency motor percentages for 6 and 8 pole motors and for motors up to 400kW.
Using these two standards, we have a high efficiency benchmark for 2 and 4 pole motors from 1.1 to 400kW and 6 and 8 pole motors from 5.5 to 315kW.
This paper will use these standards to benchmark the existing motor asset base.

Where data have been available and recorded, full load efficiencies have been calculated and are compared to the IE rating scheme.

Full load efficiencies have been calculated as follows:

Efficiency % = (Rated power x 100)/Input power (2)

and Input Power = √3 x voltage x full load current x power factor (3)

Where the data are incomplete, the IE3/IE2 boundary efficiency figure (premium/super premium) has been used, in line with IEC guidance **(De Almeida, 2011, M'Baye 2022c)**. Where the measured full load current is available, the spot percentage loading of the motor is calculated. Otherwise, 75% has been assumed.

Full load efficiencies have been used. Modern high efficiency motors tend to have a flatter load/efficiency curve than conventional motors, so the efficiency gain may well be better than assumed at less than full load, as most motors will be.

1.2.2. Motors - Survey

The survey was based upon a selection of 60 motors surveyed, for which the output power ratings of 25 were all positively identified. Some rating plates were missing, and it was not possible to view all motors for access reasons e.g., they are inside air handling units.
Blanks and/or comments in the data tables indicate where data could not be obtained.
In the survey, each motor is given a number and this number is shown in the leftmost column of each table to enable cross-reference.
Records have been created for all 60 motors.

Data collected have been analyzed to:

- Establish the motors' efficiencies and rate these against current high efficiency standards.
- Calculate potential return on investments for motor upgrades and/or variable speed drive applications.

1.2.3. Motors - Variable Speed Drives for Pumps and Fans

A VSD is an electronic device that can vary the speed of motor-driven equipment, such as a compressor, fan, or pump **(De Almeida et al., 2015)**. The VSD converts the incoming electrical supply of fixed frequency into a variable frequency output to control the motor – a low frequency for a slow speed and a higher frequency for a faster speed **(Feng et al., 2020; Saidur, 2010)**.

Electricity savings resulting from installation of variable speed drives were calculated using known relationships for percent of motor capacity as a function of percent load with and without a variable speed drive as shown in the figure 6 beside for pumps and fans. The load profiles for each VSD application that was evaluated were developed from information collected during the site visit.

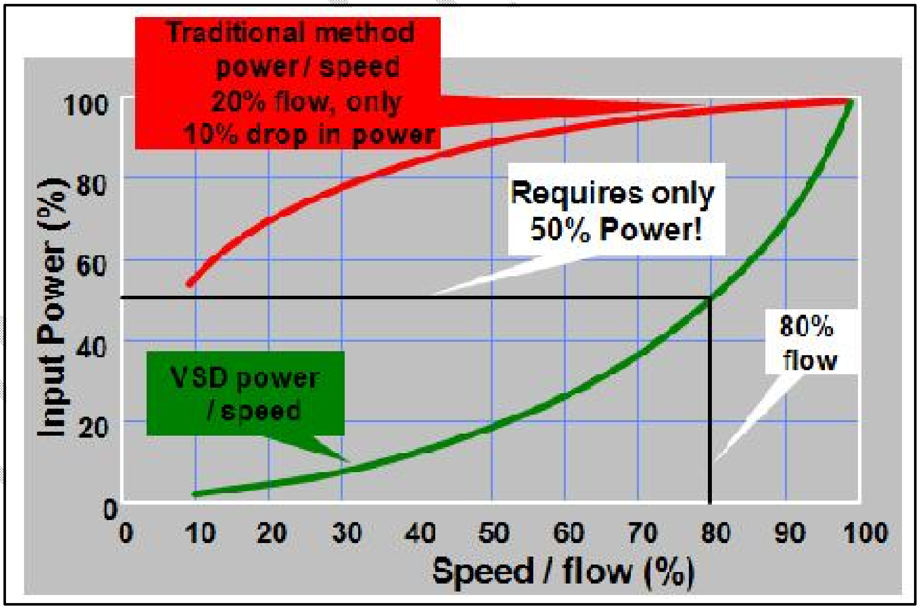

Figure 6: Relationships for percent of motor capacity as a function of percent load with and without a variable speed drive

Influence on the motor efficiency: Reducing the motor speed by using a VSD will impact the motor efficiency **(Arun et al, 2016; M'Baye 2022d)**. The coefficient used to take that impact into consideration is considered as following the curve in figure 7.

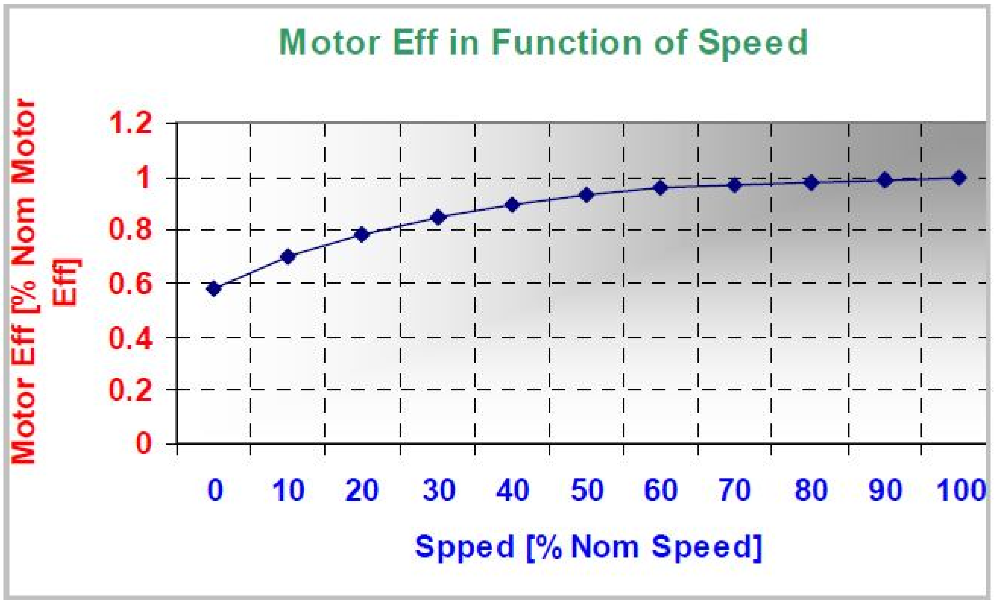

Figure 7: Motor efficiency in function of the speed

The VSD efficiencies were taken as constant whatever the frequency of regulation and equal to 97%.

1.3. Unit price and CO2 factor

On the 12-months period January 2018 to December 2018, electricity costs were $692, 954 with a consumption of 9,117,824 kWh. This gives an average price per unit of $0.076 per kWh (US dollar).

Electricity based CO2 savings have been calculated using the following emission factor: 0.089kg of CO2 per kWh consumed.

2. Result and Discussions

2.1. Metering, Monitoring & Targeting

4 meters on the main transformers must be replaced with power quality analyzer type meters to accurately detect sags, swells, power outages and over-currents. At present these cannot be detected and may have an impact on sensitive equipment if they occur.
4 additional meters must be added to the system to capture up to 700 A of energy usage.

The energy monitoring system should be expanded to log more data points, at present it only logs voltage, current and kWh. The system is currently set up to log only a small percentage of the parameters available from each meter. Harmonics should also be monitored to ensure the electricity supply is suitable for sensitive equipment.

The Energy Monitoring system is difficult to use in its current form and should be upgraded to make it more “user friendly” and allow real time energy monitoring and targeting **(Rakhmonov & Kurbonov, 2020).**
This will require nominating a member of staff to operate the system and providing training. If possible, the site should assess its existing staff structure and identify a part-time operator to

be solely responsible for collecting and monitoring energy consumption as well as utility invoice validation. Key personnel should be identified, and a report structure agreed whereby weekly/monthly reports on current performance are distributed for use with the energy awareness program. Full procedures on the operation of the monitoring & targeting (M&T) system should be kept, so that sufficient training can be given should there be any staffing restructures.

The implementation cost for the hardware (metering and communications), software upgrade and training costs are estimated to be $20,000. Table 1 includes potential savings and other important information.

Table 1 Implementation cost for the hardware and software upgrade

Recommendations	**Potential savings**				
	kWh	Dollar	KgCO2	Cost	ROI
Software upgrade	91,178	6,929	8,115	20,000	2.9

2.2. Motors

The results on motors are described in detail in this section and a discussion is included.

Table 2 contains data yields after examination (with full breakdown). It can be seen also in table 2 that of the 25 motors for which data was available to calculate an efficiency figure and benchmark. 2 motors are in classed as high efficiency.

Table 2 Data yields after examination (with full breakdown).

	Quantity	**Percentage**
Number of Motors Surveyed and rating obtained	60	100.0%
Total installed Capacity (kW)	1,083	100.0%
Number of Motors for which data was available to calculate efficiency and to benchmark	25	41.7%
Number of Motors in high Efficiency Category (IE or WIMES)	2	8.0%
Number of motors to IE1	2	8.0%
Number of motors to IE2	13	52.0%
Number of motors to WIMES HE	0	0,0%
Number of motors to IE3 or WIMES non HE	10	40,0%
Number of motors with VSD's installed	23	38.3%
Rating of Motors with VSD's installed (kW)	367	33.9%

In table 3, an estimate has been made of what the annual electricity consumption of these motors might be. This has been done using a bottom-up method - from individual consumption estimates for each motor.

Table 3 Annual electricity consumption

	kWh	**Cost $**	**KgCO2**
Estimated annual consumption by motors surveyed and rating obtained	4,340,078	329,845	386,267

Site electrical consumption (2018)	9,117,824	692,954	811,486

Motors consume typically 60% of the electrical energy on an industrial site (**De Almeida, 2014)**. Table 3 indicates that the motors in the survey account for 48% of the total consumption. However, this does not include all the motors on site i.e., the many smaller process motors, small split unit air condition units, large chillers, and large air compressors. It may however imply that the running hours and/or load factors assumed are on the conservative side. This finding is considered further in the detail of the analysis below and in the discussion of the recommendations.

The factors and assumptions used in table 2 et 3 above are shown in the table 4 below.

Table 4 Data used for the study and their recommended values

DATA USED	VALUE
Electricity Cost ($ per kWh)	0.076
kWh to kg of CO2 conversion	0.089
Motor load factor	0.75
Site annual electrical consumption (MWh)	9,118
Proportion of electricity consumed by motors	48%

High Efficiency Motor Replacement

The following procedure has been used to assess the potential energy saving and investment cost requirement for a selection of the motors if replaced with a high efficiency equivalent. From this a prospective return on investment (ROI), based on simple payback, has been calculated.

The following points have been considered:

- Where full data is not available to calculate efficiency, when relevant, the IE2/IE3 boundary rating has been used, in line with IEC guidelines. Results are annotated where this assumption has been made.
- Where actual load data is not available, a load factor of 75% is used. Results are annotated where this assumption has been made.
- Motor run hours data was obtained for each motor and was utilized to calculate the annual energy consumption and potential savings.

In the absence of full information, the replacement costs for safe area motors only have been allowed for in the calculations.

Full load efficiencies have been used in these calculations, which would make the projected savings conservative. Modern high efficiency motors tend to have a flatter load/efficiency curve than conventional motors – indeed in the IE2 class the 75% load efficiency is usually equal or slightly better than the full load efficiency. To allow for this, an adjustment to the efficiency gain has been made as follows:

- Load factor > 80% ➔ 0% increase of gain
- Load factor 60-80% ➔ 1.5% increase of gain
- Load factor <60% ➔ 3.0% increase of gain

The cost and hence ROI take no account of depreciated asset values. If some of the asset value can be written down, then the return-on-investment figures would improve accordingly. The potential annual saving has been calculated as follows:

Saving = Input power x loading% x annual hours x efficiency gain x cost/kWh (4)
Motor cost is based upon the current average price in the market supplier plus an allowance for installation.

The potential savings are summarized in table 5.

Table 5 Potential savings

Recommendations	Potential savings				
	kWh	Dollar	KgCO2	Cost $	ROI
7 No Motor replacements	45,871	3,486	4,082	7,778	2.2

Recommendations are:

- Validate the assumptions made in the calculations (particularly the running hours).
- Obtain missing motor data – take opportunities during maintenance and other intrusive activities to access the rating plates to expand the list of motors that can be analyzed.
- Prioritize replacement of the motors with annual running time ≥4,000 hours.
- Carry out a further non-intrusive audit for the rest of the motor asset base at 7.5kW rating and above.

2.3. VSD applications

The survey was based upon a selection of 60 motors. From the survey, several motors have been identified as potential applications for variable speed drives.

Based upon an average of an 11% reduction in speed, which equates to around 30% reduction in energy consumed, potential savings are calculated for each motor. The recommendations and potential savings are summarised in table 6.

Table 6 VSD applications

Recommendations	Potential savings				
	kWh	Dollar	KgCO2	Cost $	ROI
18 No VSD Applications	656,859	49,921	58,460	100,902	2.0

The comments about load factor and running hours made under Motor Replacement apply here also.

Conclusion

This paper brings to the literature a specific case study on the electrical efficiency audit. Importance and crucial role of the implementation, use and maintain of an energy Monitoring system has been demonstrated and with substantial environmental and financial savings.

The power of an Energy Monitoring System has been demonstrated through action on industrial motors as they represent a significant amount of energy consumption in industry. Other systems can be optimized following example of motors.

Opportunities identified will result in estimated savings of $60,336 per year with estimated capital expenditure (CAPEX) of $128,680 providing a Simple Payback (SPB) of 2.3 years.

Implementation of all measures would save approximately 8,7% of the current utility spend. This equates to approximately 794,000 kWh of electricity per year. Indirect Carbon dioxide savings related to this are estimated at 70.6 tons.

References

Arun Shankar Vishnu Kalaiselvan, Subramaniam Umashankar, Shanmugam Paramasivam, Norbert Hanigovszki, A comprehensive review on energy efficiency enhancement initiatives in centrifugal pumping system, Applied Energy, Volume 181, 2016, Pages 495-513, ISSN 0306-2619, https://doi.org/10.1016/j.apenergy.2016.08.070.

Cengiz, M. & Mamiş, M. (2015). Solution Offers For Efficiency and Savings in Industrial Plants . Bitlis Eren University Journal of Science and Technology, 5 (1) , 24-28 . DOI: https://doi.org/10.17678/beujst.43546

Ciulla G., D'Amico A., Building energy performance forecasting: A multiple linear regression approach, Applied Energy, Volume 253, 2019, 113500, ISSN 0306-2619, https://doi.org/10.1016/j.apenergy.2019.113500

Costa Andrea, Keane Marcus M., Torrens J. Ignacio, Corry Edward, Building operation and energy performance: Monitoring, analysis and optimisation toolkit, Applied Energy, Volume 101, 2013, Pages 310-316, ISSN 0306-2619, https://doi.org/10.1016/j.apenergy.2011.10.037

De Almeida A. T., F. J. T. E. Ferreira and D. Both, "Technical and economical considerations in the application of variable-speed drives with electric motor systems," in *IEEE Transactions on Industry Applications*, vol. 41, no. 1, pp. 188-199, Jan.-Feb. 2005, doi: https://doi.org/10.1109/TIA.2004.841022

De Almeida A. T., F. J. T. E. T. E. Ferreira and J. A. C. Fong, "Standards for Efficiency of Electric Motors," in IEEE Industry Applications Magazine, vol. 17, no. 1, pp. 12-19, Jan.-Feb. 2011, doi: https://doi.org/10.1109/MIAS.2010.939427

De Almeida A. T., F. J. T. E. Ferreira and G. Baoming, "Beyond induction motors — Technology trends to move up efficiency," *49th IEEE/IAS Industrial & Commercial Power Systems Technical Conference*, Stone Mountain, GA, USA, 2013, pp. 1-13, doi: 10.1109/ICPS.2013.6547330

De Almeida, Aníbal & Ferreira, Fernando & Duarte, Andre. (2014). Technical and Economical Considerations on Super High-Efficiency Three-Phase Motors. Industry Applications, IEEE Transactions on. 50. 1274-1285. 10.1109/TIA.2013.2272548.

Goman, V.; Oshurbekov, S.; Kazakbaev, V.; Prakht, V.; Dmitrievskii, V. Energy Efficiency Analysis of Fixed-Speed Pump Drives with Various Types of Motors. Appl. Sci. 2019, 9, 5295. https://doi.org/10.3390/app9245295

Hilliard, Antony & Jamieson, Greg. (2013). Recursive Estimates as an Extension to CUSUM-based Energy Monitoring & Targeting. 4-1..4.

Lee Dasheng, Cheng Chin-Chi, Energy savings by energy management systems: A review, Renewable and Sustainable Energy Reviews, Volume 56, 2016, Pages 760-777, ISSN 1364-0321, https://doi.org/10.1016/j.rser.2015.11.067

Mbaye, A. (2022a). Review on Energy Audit: Benefits, Barriers, and Opportunities. *American Journal of Energy and Natural Resources*, *1*(1), 45–58. https://doi.org/10.54536/ajenr.v1i1.1054

M'baye, A. (2022b). Energy Performance Management in an Industrial Site: Definition and Application of a Specific Methodology for Carbon Emissions Reduction. Low Carbon Economy, 13(03), 148-162. doi: https://doi.org/10.4236/lce.2022.133008

M'baye, A. (2022c). Carbon Emission Efficiency Best Practices: A Case Study in an Industrial Site. *Journal of Energy Research and Reviews*, *10*(3), 10–23. https://doi.org/10.9734/jenrr/2022/v10i330256

M'baye, A. (2022d). Reduction of Carbon Emissions of HVAC Systems: A Case Study of a Pharmaceutical Site in France. International Journal of Energy Engineering, 12(1), 1-14. doi: https://doi.org/10.5923/j.ijee.20221201.01

Rakhmonov I. U., Kurbonov N. N.; Analysis of automated software for monitoring energy consumption and efficiency of industrial enterprises ; E3S Web of Conf. 216 01178 (2020) ; DOI: https://doi.org/10.1051/e3sconf/202021601178

Saidur R., A review on electrical motors energy use and energy savings, Renewable and Sustainable Energy Reviews, Volume 14, Issue 3, 2010, Pages 877-898, ISSN 1364-0321, https://doi.org/10.1016/j.rser.2009.10.018

SEAI - Sustainable Energy Authority of Ireland, 2019; Accessed : 05/07/2023; https://www.seai.ie/publications/SEAI-Guide-to-Energy-MT-Final-online.pdf

Tallini Alessandro, Cedola Luca, Evaluation Methodology for Energy Efficiency Measures in Industry and Service Sector, Energy Procedia, Volume 101, 2016, Pages 542-549, ISSN 1876-6102, https://doi.org/10.1016/j.egypro.2016.11.069

Taner, T., Sivrioğlu, M., Topal, H. *et al.* A model of energy management analysis, case study of a sugar factory in Turkey. *Sādhanā* **43**, 42 (2018). https://doi.org/10.1007/s12046-018-0793-2

Van Rhyn P. and Pretorius J. H. C., "Utilising high and premium efficiency three phase motors with VFDs in a public water supply system," 2015 IEEE 5th International Conference on Power Engineering, Energy and Electrical Drives (POWERENG), Riga, Latvia, 2015, pp. 497-502, doi: https://doi.org/10.1109/PowerEng.2015.7266367