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An Electrical Efficiency Audit on a Paper Factory with a Focus on Energy Monitoring Systems and Industrial Motors

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Author's contribution

The sole author designed, analysed, interpreted and prepared the manuscript.

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ABSTRACT

Earth's average temperature continues to rise, triggering dangerous weather events that occur simultaneously and interact with each other, such as storms, floods, droughts, and wildfires. The main cause of this global warming is the excess of greenhouse gases emitted by human activities. To answer to this climate challenge, most developed countries have taken actions to reduce their carbon footprint. Industry is the third most polluting sector. This article contains research done in a paper industrial site in Belgium to reduce its carbon footprint through energy efficiency. The first part of the paper is a focus on monitoring and targeting system opportunities and barriers. The second part is about motors. Motors are generally among highest consuming equipment in an industrial site. An analysis of motors high efficiency and variable speed drive potential have been done. 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.

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1. INTRODUCTION

The greenhouse effect is a natural phenomenon, caused by the exchange of energy between the Sun and the Earth. It contributes to maintain the average level of temperature. The continuous increasing of greenhouse gases concentration in the atmosphere (related to human activities) leads to global warming. Climate change has an impact on every continent in the world (more extreme storms, floods, droughts, wildfires etc.).

For answering to this climate challenge, most of the developed countries have taken actions to reduce their carbon footprint. For example, “the European Union has set itself the goal of achieving carbon neutrality by 2050” [1].

Industry is among the most polluting sectors [2]. The first aim of this paper is to identify and evaluate the potential of CO2 savings of an energy monitoring & targeting systems on a paper industrial site.

The second aim of the article is to identify and improve the potential of CO2 savings of industrial motors as there are among the major consumption equipment in industry (and therefore among major equipment that emit more carbon).

According to Goman et al. [3], electric motors consume 46% of the world’s electricity. Cengiz & Mamiş [4] state that “motors consume an estimated quarter of the electrical energy used by manufacturing sites. However, they are often overlooked and, as a result, many sites have relatively inefficient motor operations”.

Research on motors and associated variable speed drive (VSD) have been conducted in the frame of a real case study.

The first part of the article on energy monitoring and the second part on motors are linked. In fact, to reach motors efficiency it is necessary to conduct an energy analysis with a monitoring system (when available). All the findings of the research are detailed and explained. The experimentation was held in an industrial site in Belgium.

2. MATERIALS AND METHODS

2.1 Metering, Monitoring and Targeting

“Energy savings related to implementing a good monitoring & targeting system can yield significant savings” [5]. For Lee & Cheng [6], 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.).

This system is essential to conduct energy audits and for continuous energy performance management [7-10]. According to Hasan et al. [11], an effective energy management framework not only ensures improved energy efficiency, but also optimizes the operational cost

A monitoring and targeting system must at least [12,13]:

- 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.

ISO 50001 states that an energy monitoring system is important and necessary for having the certification [14,15].

For Hussein et al. [16], Energy forecasting techniques play a significant role in energy management with a wide scope of applications, ranging from small household to huge industrial/smart grids consumption and production prediction.

It is judicious to compare energy meters data with other kind of data such as production or external temperatures (variable data). The following charts (Figs. 1, 2 and 3) illustrate how this analysis can be undertaken using a regression analysis. Figs. 1, 2 and 3 have been done with Microsoft Excel software as it is a powerful and user-friendly software.

As represented in Fig. 1, by plotting electricity versus production, a linear trend line (linear regression) can be drawn [17,18]. In this example (Fig. 1), we can clearly see that the production increase triggers an electrical consumption increase (and vice versa in case of decrease).

Linear regression of Fig. 1 is obtained through the equation below:

$$\mathbf{y = mx + c} \tag{1}$$

- 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.

The equation (1) becomes the target and can be further analyzed as a CUSUM (Cumulative Sum) graph as represented in Fig. 2.

In Fig. 2, we can also see that energy performance was worse than the baseline during Q1 2016. It gradually improved during Q2. This was followed by a period that was significantly better than the baseline up to November 2016. During December 2016, something occurred to reverse this trend and energy performance was again worse than the baseline, as indicated by the fact that the line is again trending upwards [18].

According to Taner et al. [19], “CUSUM is a numerical calculation for energy consumption analysis that determines the annual energy efficiency for factories”.

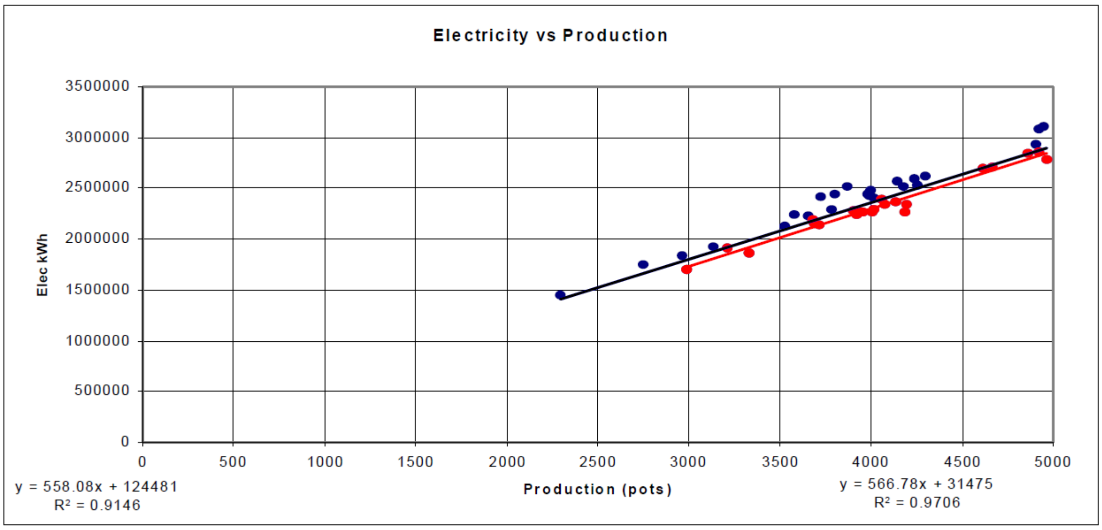

Fig. 1. Example of linear regression analysis

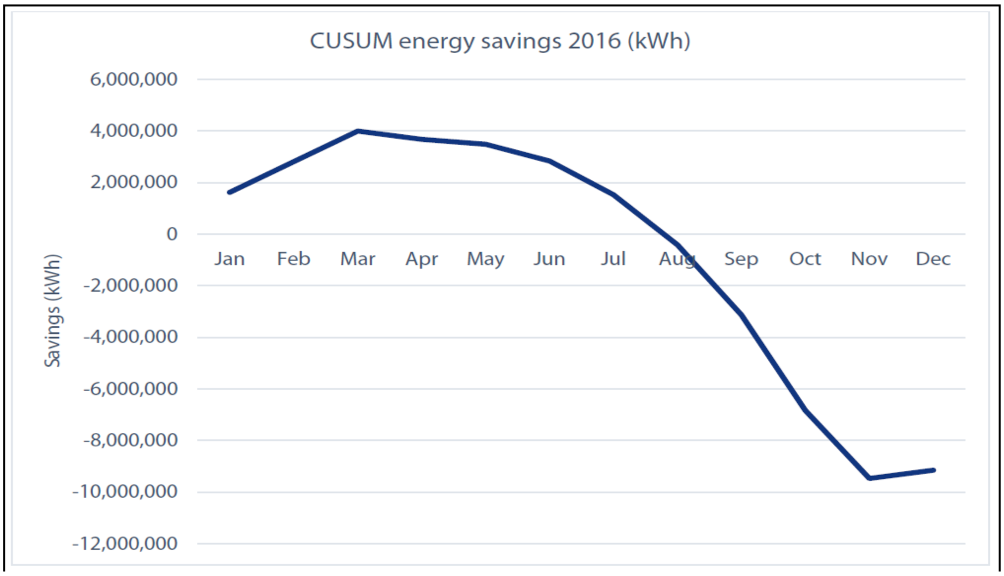

Fig. 2. CUSUM electric arc furnace example [19]

"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" [20].

The site has an existing metering & monitoring system, (Factory Talk Energy Metrix software by Allen Bradley) 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.

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 Fig. 3.

The CUSUM analysis for the site energy usage compared to the production is represented in Fig. 4 (chart done also with Microsoft Excel software).

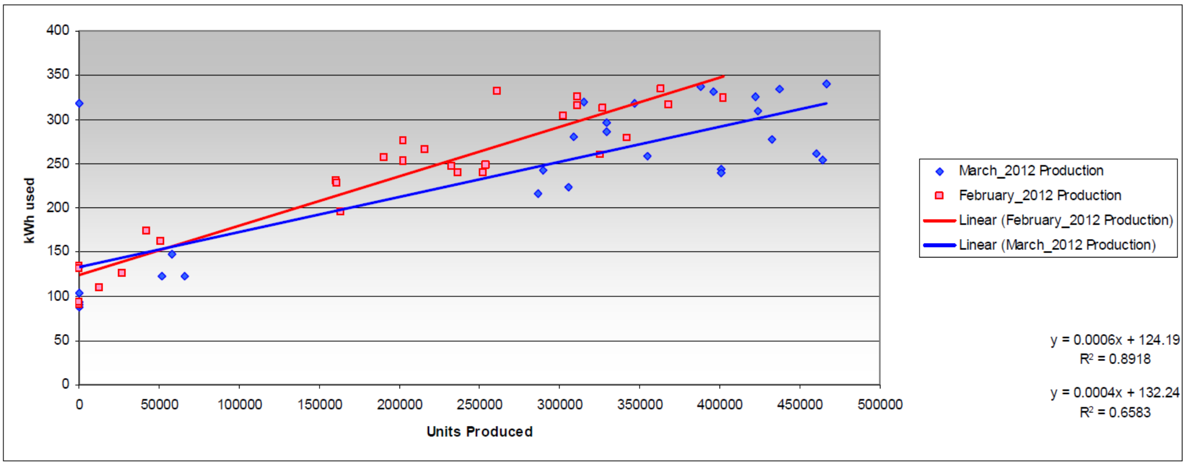

Fig. 3. Electricity and production linear regression analysis for February and March 2012

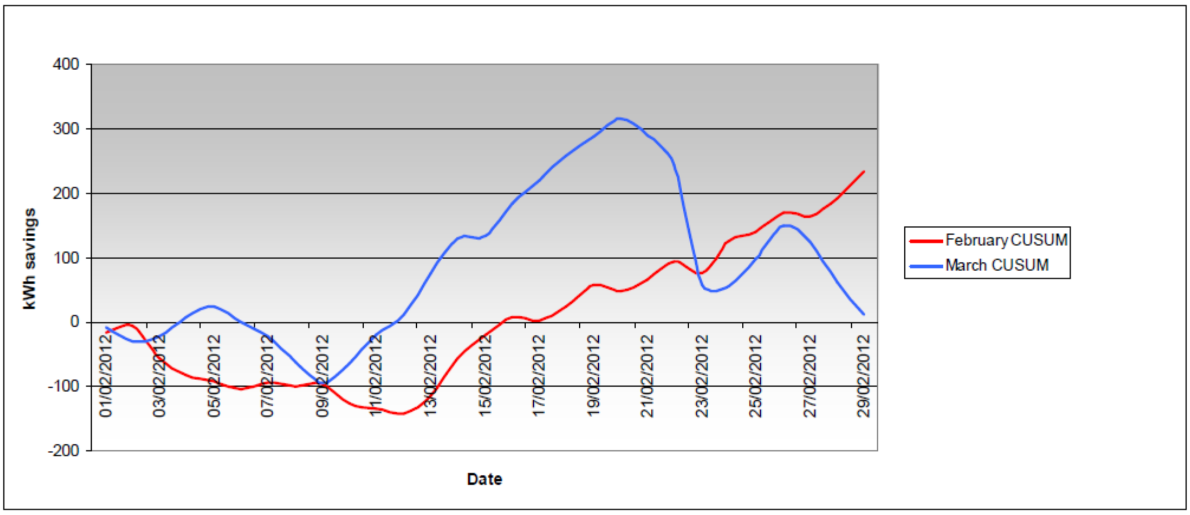

Fig. 4. CUSUM analysis for the site energy usage compared to the production for February and March 2012

The above charts (Figs. 3 and 4) 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.

In 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.

2.2 Motors

Motors - high efficiency definition: Van Rhyn & Pretorius [21] 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 Fig. 4 contains the efficiency of each class following motor rated power.

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:

$$\text{Efficiency \%} = (\text{Rated power} \times 100)/\text{Input power} \qquad (2)$$

and

$$\text{Input Power} = \sqrt{3} \times \text{voltage} \times \text{full load current} \times \text{power factor} \qquad (3)$$

Where the data are incomplete, the IE3/IE2 boundary efficiency figure (premium/super premium) has been used, in line with IEC guidance [23, 24]. 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. Therefore, the efficiency may be better than assumed below full load.

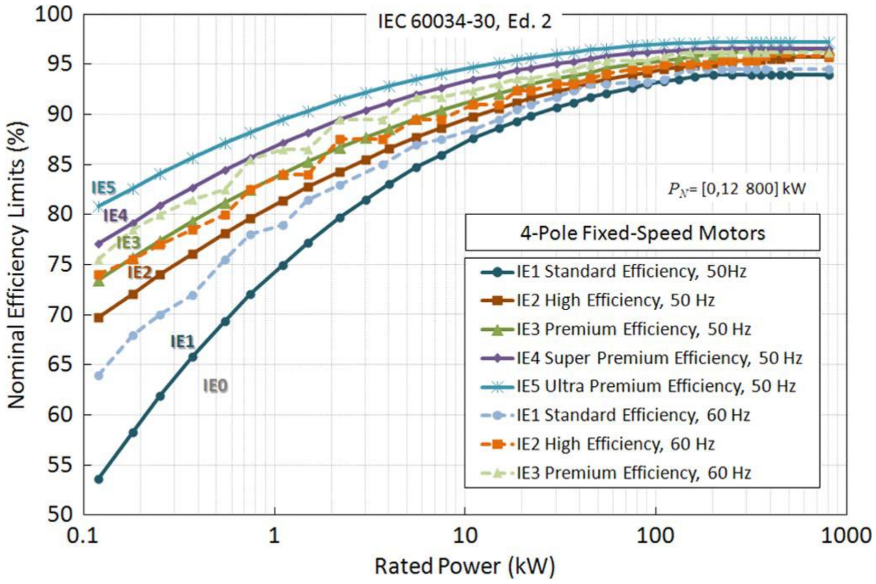

Fig. 5. IEC 60034-30 nominal efficiency class limits, for four-pole motors [22]

Motors – survey: The survey was based upon a selection of 60 motors surveyed, for which the output power ratings (and other data) of 25 were all positively identified on the field. 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.

The factors and assumptions used in the research are indicated in the Table 1.

Table 1. Data used for the study and their recommended values

Factors & assumptions 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%

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" [25, 26]. "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" [27].

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 Fig. 6 beside for pumps and fans. As shown also in Fig. 6, a 20% speed drop with a motor without VSD leads to 10% power drop whereas a motor fitted with VSD leads to a 50% power drop.

The load profiles for each VSD application that was evaluated were developed from information collected during the site visit.

Influence on the motor efficiency: As demonstrated by M'baye [28] and Arun et al. [29] in their research, reducing the motor speed by using a VSD will impact the motor efficiency. The coefficient used to take that impact into consideration follows the curve in Fig. 7: For a speed decrease from 100% to 40%, motor efficiency drops by 10%; Below 40% of speed, motor efficiency drop is accelerating.

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

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.

3. RESULT AND DISCUSSION

3.1 Metering, Monitoring and 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. Now, they 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. Currently, 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 [30].

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 [31].

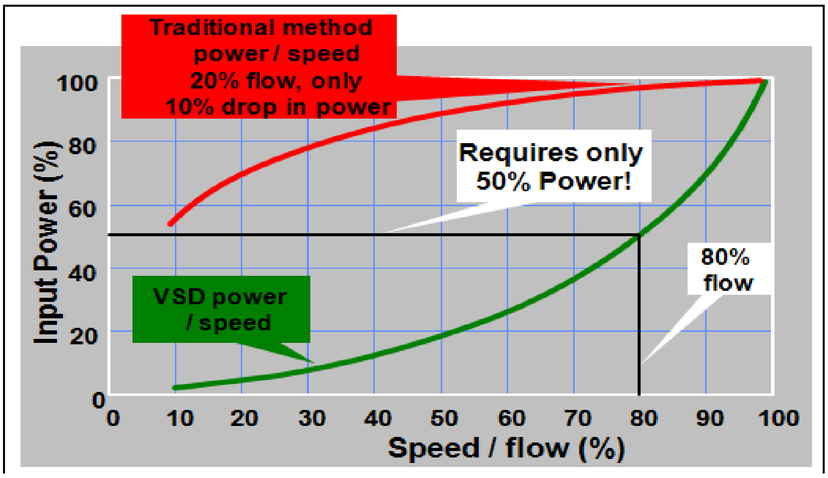

Fig. 6. Relationships motor's power and motor's speed with and without a variable speed drive

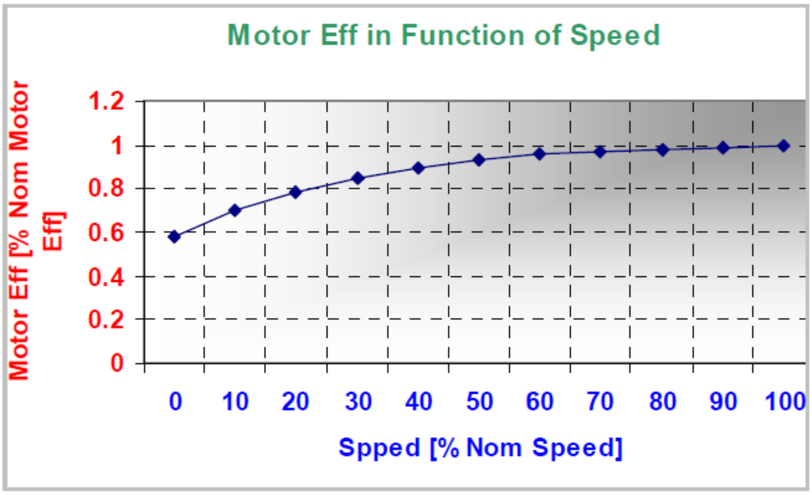

Fig. 7. Motor efficiency in function of the speed

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 2 includes potential savings and other important information.

3.2 Motors

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

Table 3 contains data yields after examination (with full breakdown). It can also be seen in Table 3 that data was available for 25 motors and that 2 motors are classed as high efficiency motors.

In Table 4, an estimation has been made of motors annual electricity consumption. This has been done by using the bottom-up approach (individual consumption estimates for each motor).

Table 2. **Implementation cost for the hardware and software upgrade**

Recommendations	Potential savings				
	kWh	Dollar	KgCO2	Cost $	ROI
Energy software upgrade	91,178	6,929	8,115	20,000	2.9

Table 3. 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%

Table 4. 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 [32]. Table 4 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.

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 [33,34]:

- Where full data is not available to calculate efficiency and 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.

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 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

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

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

As demonstrated by M'baye [35], electronically commutated (EC) motor should be the first choice when replacing motors or/and implementing VSD as savings are significant with this type of motors

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.

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.

3.3 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 indicated in Table 6.

4. 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.

COMPETING INTERESTS

Author has declared that no competing interests exist.

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