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Article

Using Field Data for Energy Efficiency Based on Maintenance and Operational Optimisation. A Step towards PHM in Process Plants

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Abstract: Energy saving is an important issue for any industrial sector; in particular, for the process industry, it can help to minimize both energy costs and environmental impact. Maintenance optimization and operational procedures can offer margins to increase energy efficiency in process plants, even if they are seldom explicitly taken into account in the predictive models guiding the energy saving policies. To ensure that the plant achieves the desired performance, maintenance operations and maintenance results should be monitored, and the connection between the inputs and the outcomes of the maintenance process, in terms of total contribution to manufacturing performance, should be explicit. In this study, a model for the energy efficiency analysis was developed, based on cost and benefits balance. It is aimed at supporting the decision making in terms of technical and operational solutions for energy efficiency, through the optimization of maintenance interventions and operational procedures. A case study is here described: the effects on energy efficiency of technical and operational optimization measures for bituminous materials production process equipment. The idea of the Conservation Supply Curve (CSC) was used to capture both the cost effectiveness of the measures and the energy efficiency effectiveness. The optimization was thus based on the energy consumption data registered on-site: data collection and modelling of the relevant data were used as a base to implement a prognostic and health management (PHM) policy in the company. Based on the results from the analysis, efficiency measures for the industrial case study were proposed, also in relation to maintenance optimization and operating procedures. In the end, the impacts of the implementation of energy saving measures on the performance of the system, in terms of technical and economic feasibility, were demonstrated. The results showed that maintenance optimization could help in reaching an energy costs recovery equal to the 10% of the total costs for an electric motor system.

Keywords: energy efficiency; maintenance optimization; conservation supply curve

1. Introduction. A Framework for the Energy Efficiency Improvement

Manufacturing companies, and process plants within them, can define their strategies and competitive priorities on different key performance indicators for their production systems: flexibility, productivity, quality, but also safety, environmental protection, and energy efficiency.

Maintenance is fundamental in assuring the availability and reliability of production facilities; thus, if Companies design proper maintenance policies—which are a set of rules describing the triggering mechanism for the different maintenance actions—they could more easily reach their productivity goals and guarantee plants efficiency. Complex process plants contain several major-energy consuming equipment, and thus offer multiple opportunities for energy saving, that

Worrell et al. [1] linked to a significant boost to the overall industrial productivity, as demonstrated by the review of more than 70 industrial case studies. As stated in [2], evidences suggest that energy efficiency measures imply improvements in economic performances.

To gain the above discussed benefits, most of all for plants where the energy efficiency policy is still under development, it is important to define a prioritization criterion for the multiple energy efficiency measures that could be identified, leading to a maximization of the implemented measures efficacy.

In this paper, a framework is proposed (Figure 1) that is able to guide plant technicians in initiating and following up this course, through the exploitation of the full set of information available in the plant.

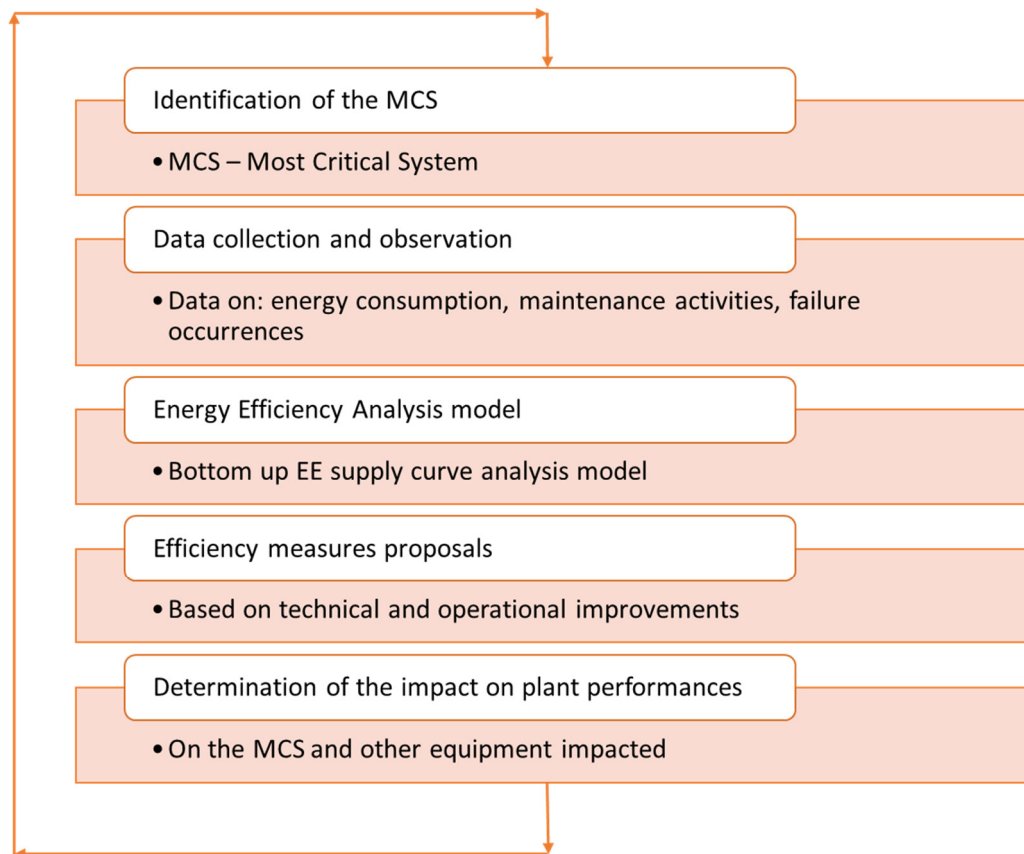


Figure 1. Scheme of the adopted framework.

The scheme in Figure 1 can be summarized as follows:

- A. Identification of the most critical system. Depends on the energy consumed by the single equipment or system.
- B. Data collection and observation. Lifetime observation and data collection about energy consumption, corrective and preventive maintenance activities, and failures occurrence. It includes the maintenance costs estimation, the economic evaluation of maintenance policies, and the estimation of the operating costs of the system.
- C. Energy Efficiency model. Analysis of the energy efficiency benefits, using an energy efficiency model, as further discussed in Section 2.
- D. Efficiency measures proposal. Definition of scenarios and efficiency measures.
- E. Determination of the impact of the proposed measures on the performance of the plant, when considering both the equipment under analysis and other pieces of equipment or systems that could be affected by the measures implemented.

The analysis is then reiterated for all the energy critical systems of the plant.

Points D. and E. will be detailed in Section 3, while Section 4 will demonstrate the whole process through the application to a bituminous material process plant.

2. Energy Efficiency Models

Current analysis of energy consumption in process plants is mostly performed through process simulations, allowing for considering the effect of some factors affecting energy consumption, as operating conditions, raw materials, fuel, and yield [3]. These methodologies require a huge amount of data and are recognized to be inefficient in speculating factors that affect energy consumption.

The same authors thus discussed different index analysis methods to analyze energy efficiency—as Data envelopment analysis (DEA), which gained great popularity in energy literature because it is a non-parametric approach dealing with multiple inputs and outputs that allow assessing relative energy efficiency [4]. However, they were judge unable to produce a complete picture of the energy efficiency measures impact in terms of energy consumption, energy saving potential, and economical gain.

The proposed solution in [3] is an integrated approach, which uses IDA—Index Decomposition Analysis [5]—to analyze changes in energy consumption over time and energy saving potential method [6], in order to highlight both the technological and the structure energy-saving potential. This approach was applied to an ethylene production case, identifying the improving measures for raw materials; however, it could not determine the specific improvement for the production structure. Furthermore, the application of the system appeared quite complex and data intensive.

A simpler approach is the CSC (Conservation Supply Curve), which assesses the cost effectiveness and the technical chances for energy efficiency. The energy conservation potential is shown as a function of the marginal CCE (Cost of Conserved Energy), and provides a clear visualization of energy efficiency.

CSCs were first introduced by Meier at Lawrence Berkeley National Laboratory [7]. Later, they were used in various studies to capture energy efficiency potentials in different economic and industrial sectors [8–12]. CSC was chosen for the purpose of the present analysis framework.

CCE allow for making explicit the impact of maintenance and productivity optimization on energy saving, according to Equations (1) and (2).

$$CCE = \frac{I \times q + M\&O}{S}, \quad (1)$$

$$q = \frac{d}{\left(1 + (1 + d)^{-n}\right)}, \quad (2)$$

CCE is the cost of conserved energy for the energy efficiency measure in €/kWh, I is the capital cost in €, q is the capital recovery factor, y^{-1} , $M\&O$ is the annual change in Maintenance and Operation costs in €/y, S is the annual energy saving in kWh/year, d is the discount rate, and n is the lifetime of the conservation measure, in y.

Maintenance and operations optimization can bring to a reduction in $M\&O$, but also in capital costs, I , with an increased effect on CCE.

Three classes of costs compose the $M\&O$ factor: (i) Fixed operational costs; (ii) Variable operational costs; and, (iii) Unavailability costs [13], as shown in Equation (3):

$$\text{Total } M\&O \text{ cost} = \text{Fixed cost} + \text{Variable cost} + \text{Unavailability cost}, \quad (3)$$

Fixed costs for Maintenance and Operation include plant operator's wages, general and equipment maintenance costs, insurance and taxes. The variable part of $M\&O$ costs includes expenses that are dependent on the amount of production or on the equipment operation time. Both classes

strictly depend on the maintenance policy of the process plant. Unavailability costs are related to the failure of the equipment and on the lack of production following the plant stop.

3. Energy Efficiency Measures Identification and Optimization

The procedure for the identification of the efficiency measures and their optimization on the basis of CCE is here described. With respect to literature methodologies, our research focused the attention not only on the technical measures to increase energy efficiency, but also on the effect of maintenance and operational management of the plant itself. Thus, it has to be considered that, depending on the initial level of maintenance policy and operational management, the energy recovery capabilities will change, decreasing at the increasing of the maintenance and operational management capacity of the company considered.

Three different base case scenarios—Low, Medium, and High—were hypothesized for energy efficiency, each of them with a decreasing potential energy recovery related to the optimization of maintenance activities and operating procedures, as in Table 1.

Table 1. Efficiency base case scenarios.

| Efficiency Base Case Scenarios | Characteristics | Possibility of Energy Recovery |
|--------------------------------|--|--------------------------------|
| Low Level | Maintenance policy is mainly reactive and limited to operations' continuity. | 15% |
| Medium Level | Maintenance policy is mainly reactive, but includes some preventive actions. | 10% |
| High Level | Both routine and predictive maintenance are practiced. | 5% |

The levels of efficiency base case scenarios, with their relative potential of electricity power recovery based on maintenance activities, are defined through expert opinion and data obtained from the literature.

In general terms, Table 1 should be built for each piece of equipment or system to be considered for optimization, combining observable data with expert opinions to allow for developing energy efficiency supply curves.

The first step should be a literature review to gain an initial set of information, to be enriched with expert knowledge. The procedure could be summarized as follows:

- (1) development of a baseline information from literature and technical data;
- (2) energy audit and data collection;
- (3) expert knowledge input; and,
- (4) definition of base efficiency scenarios and proposal of operational and technical measures of improvement.

After calculating the CCE for all of the energy efficiency measures proposed, the measures are ranked in ascending order of CCE, against an energy price line. All measures that fall below the energy price line are cost-effective. On the curves, the width of each measure (plotted on the *x*-axis) represents the annual energy saved by that measure. The height (plotted on the *y*-axis) shows the measure's cost of conserved energy.

Scientific and technical literature can be used for an initial screening, e.g., in Abdelaziz et al. [14] and Bunse et al. [15] or Therkelsen and McKane [16] a general dissertation of the energy efficiency measures that can be adopted in the industrial domain can be found.

The measures related to the maintenance and operational control could be summarized in three main families:

- enhancement and upgrading of existing maintenance procedures;
- adoption of new technologies and more efficient devices; and,

- design of a predictive maintenance program.

A growing interest is evident in the development and modeling of maintenance activities, as in Zio and Compare [17] or Faccio et al. [18]. Predictive maintenance requires that models and tools able to predict the breakdown of the system to be maintained, by detecting early signs of failure, as in Rosmaini and Kamaruddin [19]. Acting before failure allows for solving any fault, even if there is no immediate danger; this proactive maintenance ensures smooth operation and reduces energy consumption. Predictive maintenance techniques are closely associated with sensor technologies, but a comprehensive approach, integrating sensing with subsequent maintenance activities, is needed to increase their efficiency.

Recent advances in information, communication, and computer technologies, as Internet of Things and RFID (radio-frequency identifications), support prognostic and health management philosophy and make predictive maintenance applications more efficient, applicable, affordable, and consequently more common and available for different industrial domains [20].

4. Bitumen Processing Case Study

The plant object of the study is a process to produce modified bitumen, as in Figure 2.

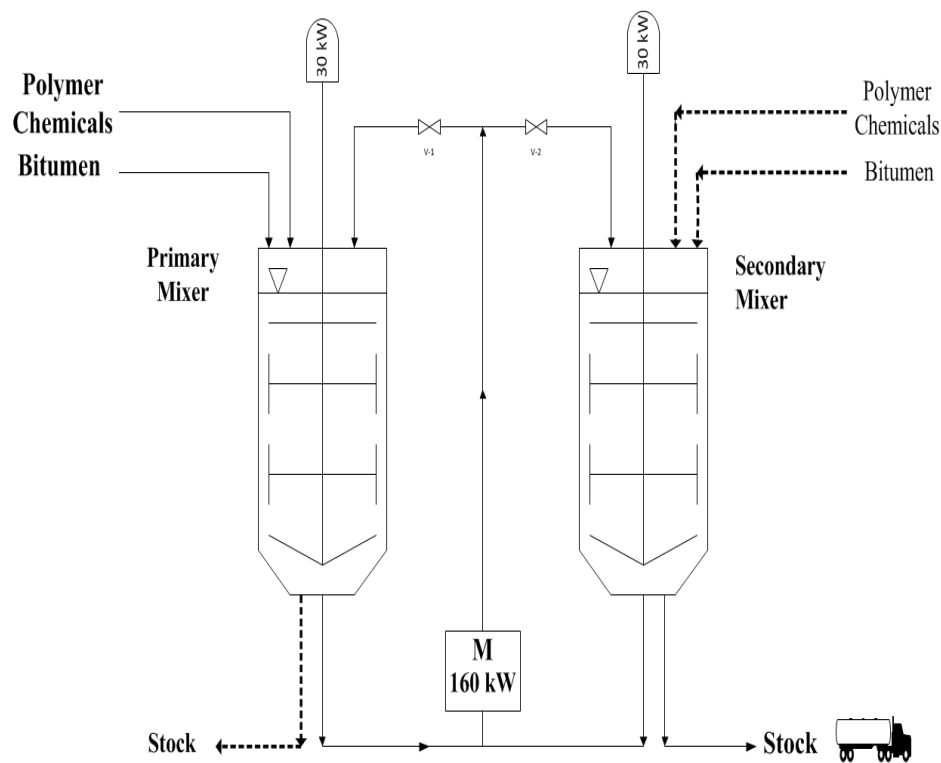


Figure 2. Batch production process of modified bitumen.

It produces 20–21 t/h of modified bitumen. The plant is made of two mixers, the primary and the secondary one. The operation of the mixers is switched every year.

Bitumen, together with polymer and other chemical additives, is fed to the primary mixer and mixed up until the expected quality of the product is obtained.

In the end, the mixture passes in the secondary mixer, which operates the final homogenization: the final product is modified bitumen with high quality and performances.

After a laboratory quality control, the product is stored waiting for the delivery to the costumers.

4.1. Data Collection and Observation

With reference to the framework detailed in Section 1, the most critical system was identified: a three-phases electric motor was the main energy consumer in the analyzed process. The motor drags the mill for the polymer homogenization to a rotation speed of about 1800 rpm.

Typical motor energy absorption is shown in Figure 3. A peak of energy absorption of about 400 A is present at the startup of the motor, for around 5 s. In case the motor works unloaded, it absorbs little electricity power, while when it works under load it shows an almost constant absorption, which depends on the motor efficiency, the viscosity of the product, and other parameters.

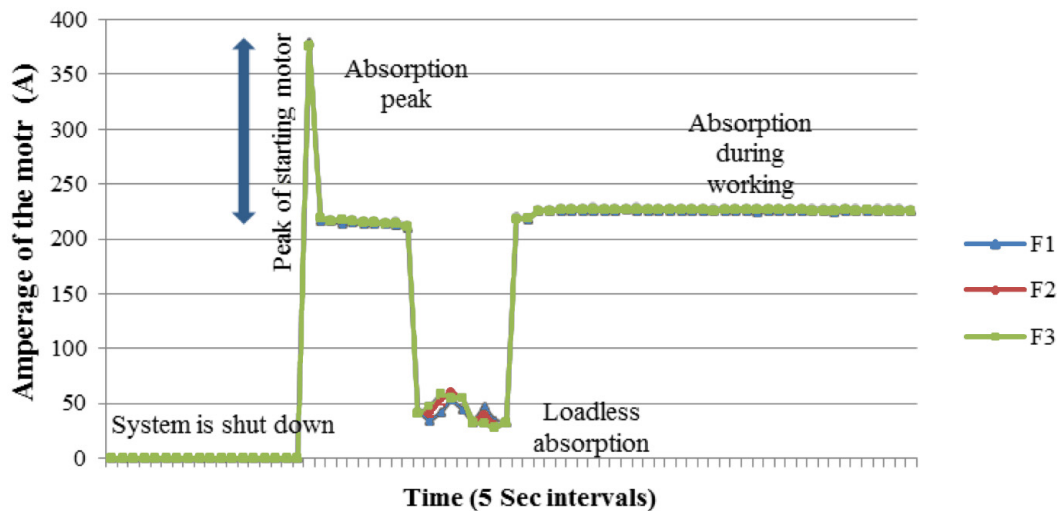


Figure 3. Typical electrical energy absorption of the motor.

The company was already monitoring the energy absorption of the plant, but these data were not employed for decision making in terms of process optimization.

Thus, in this research, the recorded data were used to analyze the energy footprint and to define possible efficiency measures to increase the performances of the system. This knowledge was integrated with the analysis of the maintenance activities and failures occurrence related to the observed motor system.

In July 2010, the motor failed after 8000 h (4 years) working: moisture inside the motor dripped on the terminal block burning it. During the starting, the motor showed anomalies, particularly in one of the phases, and after few minutes, it stopped.

A new motor was available in the stock, so the loss of production following the failure was limited to the 10 h that was needed for the substitution. Figure 4 shows the electric energy absorption trend of the motor, before failure. It shows regular cycles, each of 1 h, with a maximum consumption of 230 A.

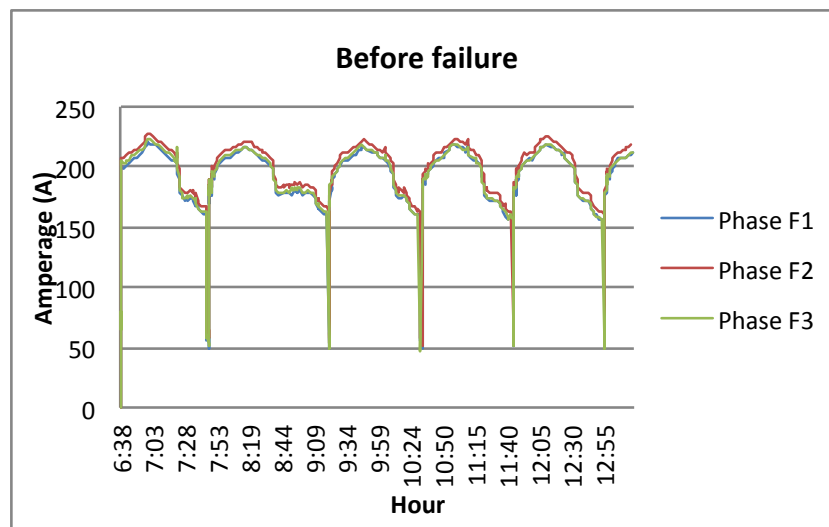


Figure 4. Absorption trend of the old motor before failure.

The motor efficiency was about 89%, as estimated by plant technicians.

Figure 5 shows the trend of energy absorption of the motor when the failure occurred:

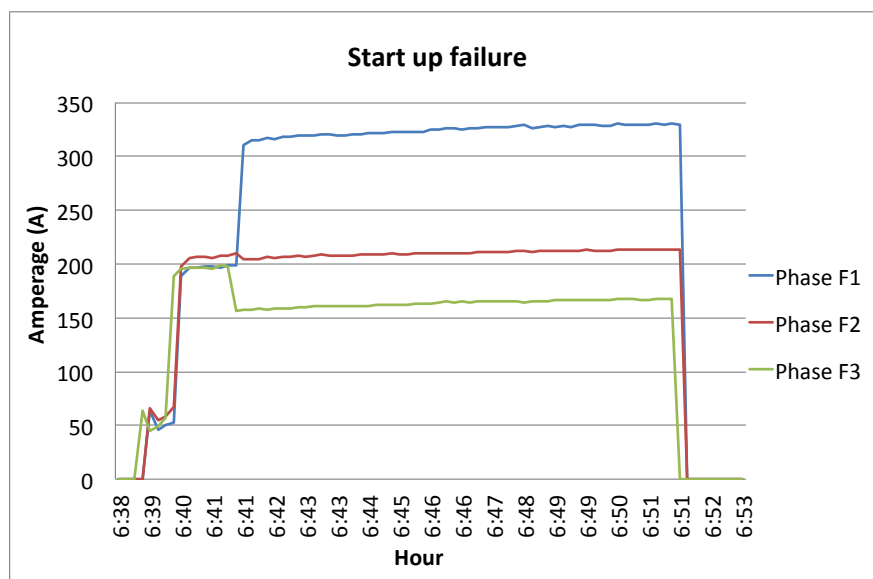


Figure 5. Trend of energy absorption of the old motor during breakdown.

Following the failure, a new motor was installed, which was characterized by an efficiency of the 96%, as estimated by plant technicians. Energy absorption trend of the new motor is shown in Figure 6. The working consumption was around 150 A.

4.2. Economic Evaluation of Maintenance and Operating Costs

Maintenance and Operational costs model, as shortly discussed in Section 2, was used to estimate total M&O parameter for the motor system.

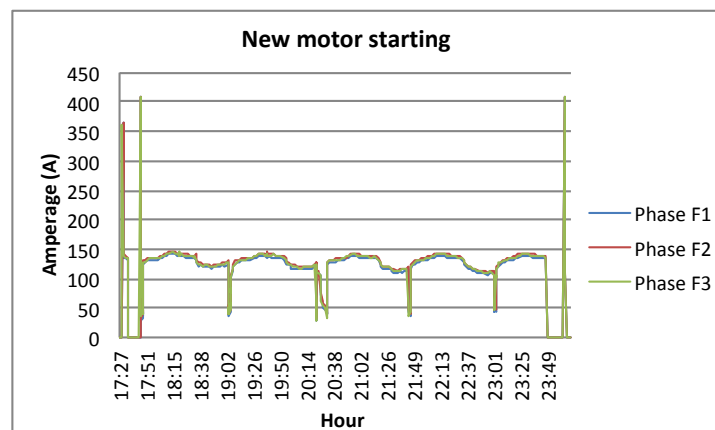


Figure 6. Trend of energy absorption of the new motor.

4.2.1. Maintenance Costs

The maintenance activities carried on in the plant are both preventive and corrective, as summarized in Table 2, while Table 3 shows the estimated costs of maintenance activities according to Equation (3) and company data.

Table 2. Maintenance activities.

| Type | Action | Interval | Duration |
|------------|--|----------|----------|
| Preventive | Terminal block tightening | 2 months | 10 min |
| | Bearings greasing | 1 months | 5 min |
| | Belts tensioning | 1 months | 5 min |
| | Mill cleaning | 1 year | 2 h |
| Corrective | Old motor repair | – | – |
| | Transport damages repair | – | 10 h |
| | Plant unavailability during motor substitution | – | – |

Table 3. Estimated maintenance activities costs.

| Motor System | Year | Cost of Maintenance Activities (€) | |
|------------------------------------|------|------------------------------------|------------|
| | | Preventive | Corrective |
| Old Motor | 2008 | 5130.95 | - |
| | 2009 | 5295.35 | - |
| Old Motor failure and substitution | 2010 | 6110.15 | 2095 |
| | 2011 | 2922.10 | - |
| New Motor | 2012 | 4401.55 | - |

Preventive maintenance costs showed a slight increase during the years, due to the cost of work increase. When the new motor was activated, its preventive maintenance for the first year was very limited (in actions and costs), and then it increased in the second year of activity. From the second year on, the progress of the costs for preventive maintenance actions became only dependent on the cost of the work.

4.2.2. Operating Costs

Operating costs of the motor were calculated, based on the data collected in 2010, 2011, and 2012. Different factors can affect the operating costs; the average production capacity, the operational hours—depending on the period of the year—and the average cost of electricity were considered.

The total electricity that is used by the plant is about 1.3–1.4 GWh in a year and the total electricity used by the motor is about 23% of the total energy. Table 4 summarizes the costs of operation as retrieved by plant monitoring.

Table 4. Operation costs of the motor.

| Year | Average Production Capacity (t/h) | Average Electricity Cost (€/kWh) | Average Working Hours of Motor (h) | Average Electric Consumption of Motor (kWh) | Average Cost of Motor Consumption (€) |
|------|-----------------------------------|----------------------------------|------------------------------------|---|---------------------------------------|
| 2010 | 20.17 | 0.137 | 1958 | 239,504 | 32,971.07 |
| 2011 | 20.39 | 0.149 | 2528 | 300,154 | 44,891.85 |
| 2012 | 20.27 | 0.165 | 2250 | 267,154 | 44,535.77 |

On the basis of the data of Table 4 and of the monthly trend of energy consumption of the company, Figure 7 shows monthly trends of motor electricity consumption, and Figure 8 shows monthly trends of the power consumption costs.

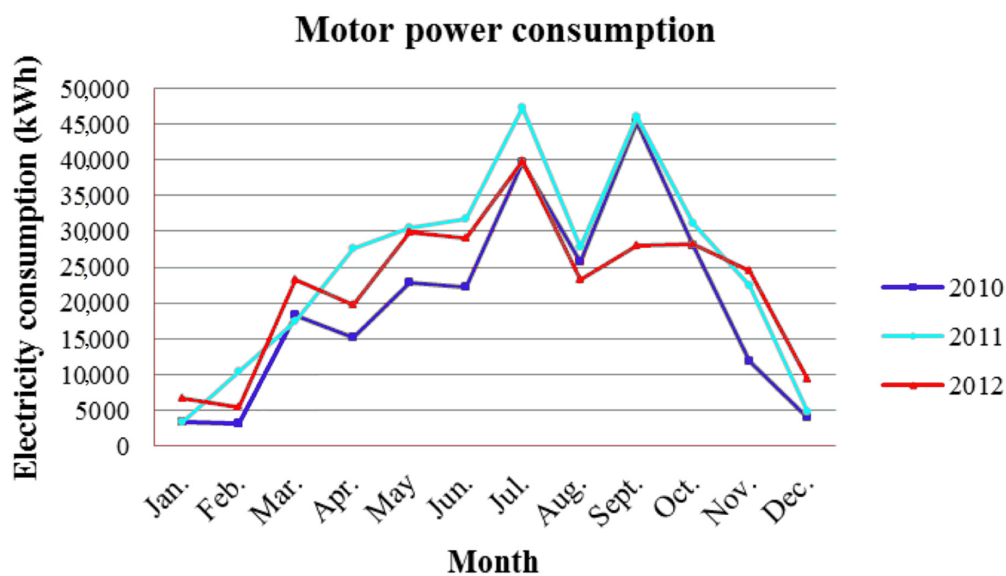


Figure 7. Power consumption of the motor—monthly data.

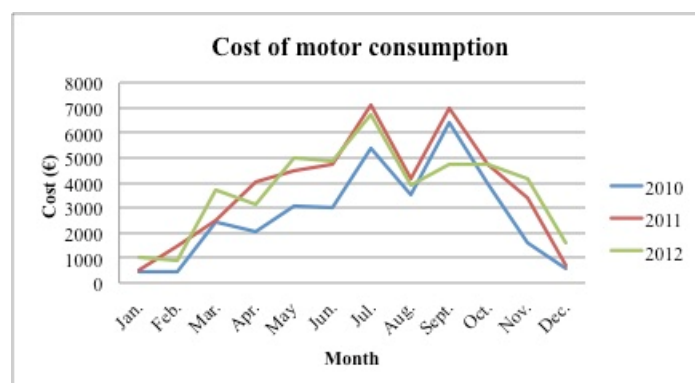


Figure 8. Costs of motor power consumption—monthly data.

4.3. Efficiency Analysis

The knowledge base collected in previous sections was used to estimate the gain obtained with the maintenance and operation optimization.

The energy saving achieved by the implementation of each single measure was assessed on the bases of the following inputs:

- (1) The efficiency base case scenarios for motor system, as discussed in Section 3.
- (2) The measures proposed to increase the energy efficiency of the motor system, together with the possible % improvement, according to the different scenarios.
- (3) The annual electricity used by the motor system.

According to Equation (1), the CCE for each base case scenarios was calculated for the three years 2010–2012, as shown in Figure 9, assuming: an average annual energy consumption of 300,000 kWh over the three years, the same average energy price, 0.15 €/kWh, and the same capital recovery factor, 0.922, in each year.

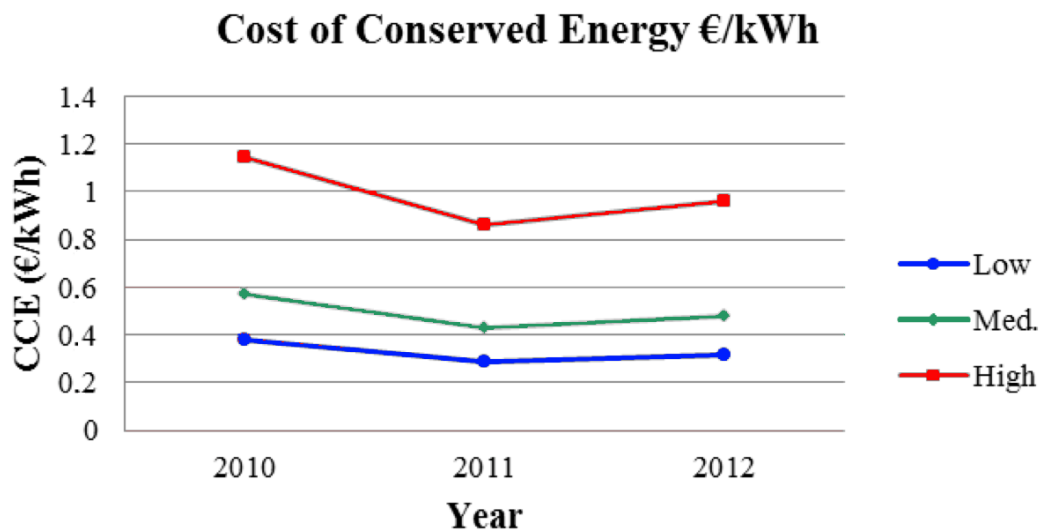


Figure 9. Annual trends of cost of conserved energy for three efficiency base case scenarios—constant discount rate.

The interest rate assumed in our simulations was 3% and the discount rate d was 0.75% per year, in order to reflect the barriers to energy efficiency investment—as perceived risk, lack of information, management concerns about production, and capital constraints, within others.

The discount rate can be a relevant parameter for a sensitivity analysis. Figure 10 shows e.g., the effect in case the real discount rate is used: a value of d of 1.25 in 2010 brings to a q of 1.37, while for the years 2011 and 2012, the d value of 0.75 is maintained (with a consequent value of q of 0.922). Thus, CCE for 2010 appears higher than for the following years [21].

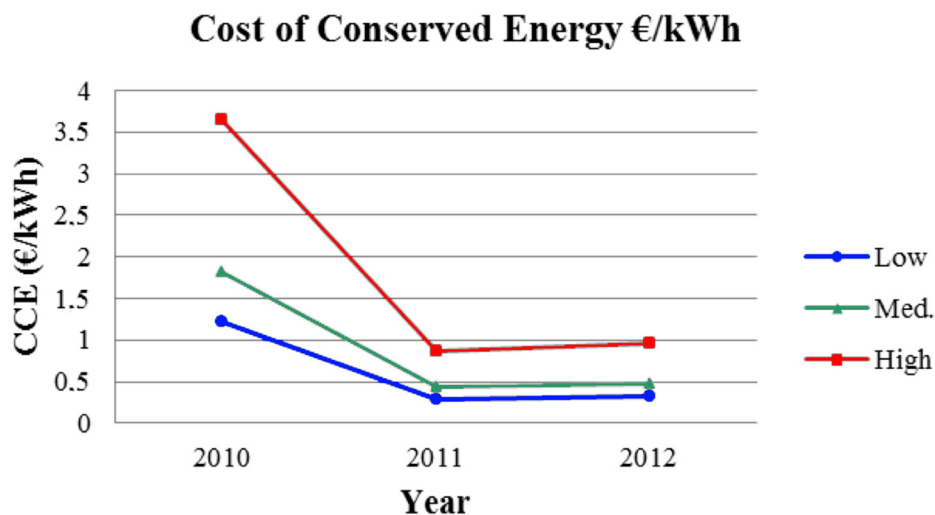


Figure 10. Annual trends of cost of conserved energy for three efficiency base case scenarios—real discount rate.

4.4. Efficiency Analysis

Expert opinion and data obtained from literature were used to choose efficiency measures and to construct a preliminary efficiency recovery for motor system based on maintenance activities, operating procedures, and conditions of the system (technical and economic feasibility).

For industrial motors, the literature related to the measures is quite rich: De Almeida et al. [22] discussed about potentials, barriers, and solutions; Sola et al. [23] developed a whole dedicated model; more specific indications can be found in Singh et al. [24], McKane and Hasanbeigi [25], and Zubergi et al. [26].

Table 5 shows the percentage of improvement in energy efficiency. The suggested measures are prioritized according to company policies.

Since the system under analysis fell within the medium potential for energy recovery, because the plant already implemented preventive maintenance measures, the cost of conserved energy CCE for the Medium base case scenario was calculated accordingly (10%).

Table 5. Efficiency improvement % over each base case scenario for the electric motor system (case study).

| Energy Efficiency Measure | Potential Energy Recovery | | | I (€) | M&O (€) |
|---|---------------------------|------|------|-------|---------|
| | Low | Med. | High | | |
| 1. Maintenance upgrading—Fix leaks, damaged seals and packing | 3.0 | 2.0 | 1.0 | 200 | 100 |
| 2. Maintenance upgrading—Remove sediments from mixer | 7.0 | 5.0 | 3.0 | 1500 | 700 |
| 3. Hardware improvement—Replace Motor with more energy efficient type | 14.0 | 7.0 | 5.0 | 6000 | 0 |
| 4. Hardware improvement—Use of new technologies and more efficient devices, like: new belts with higher power transition and maintenance free | 1.0 | 1.0 | 1.0 | 303.7 | -300 |
| 5. Maintenance advancement—Initiate predictive maintenance program | 7.0 | 5.0 | 2.0 | 2000 | 200 |
| 6. Hardware improvement—Use of inverter or variable speed drive | 8.0 | 5.0 | 2.0 | 5000 | 0 |
| 6a. Operational optimization—management of motor consumption, to minimize peaks at work start/stop | 5.0 | 2.0 | 1.0 | 250 | 0 |

4.5. Conservation Supply Curve

Figure 11 shows the procedure according to which the calculation and data analysis was carried out. In this approach, as illustrated in detail by McKane and Hasanbeigi [25], the measures were initially treated in isolation, and then, with a refined calculation, their mutual relation was considered. The annual electricity saving obtainable by each individual efficiency measure was estimated by using

Equation (1). 2010 was used as reference year for the estimation, so in the economic analysis a constant cost of energy of 0.15 (€/kWh) was considered.

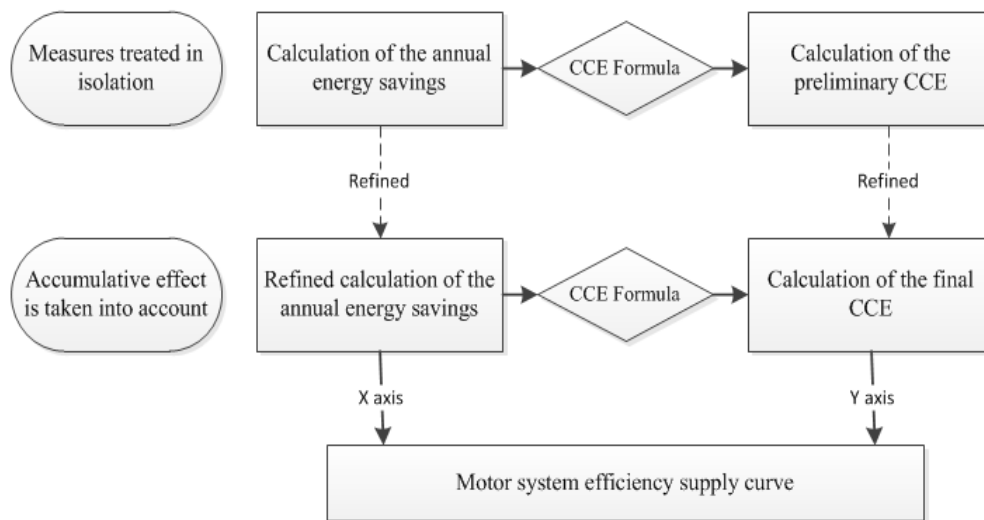


Figure 11. Procedure of the Conservation Supply Curve (CSC) calculation.

Figure 12 shows the resulting CSC as a function of the marginal CCE, taking into account the costs that are associated with the implementation of the measures in Table 6, that explicitly accounts for the maintenance and operation costs. The technical electricity saving potential is 43,189 kWh/year.

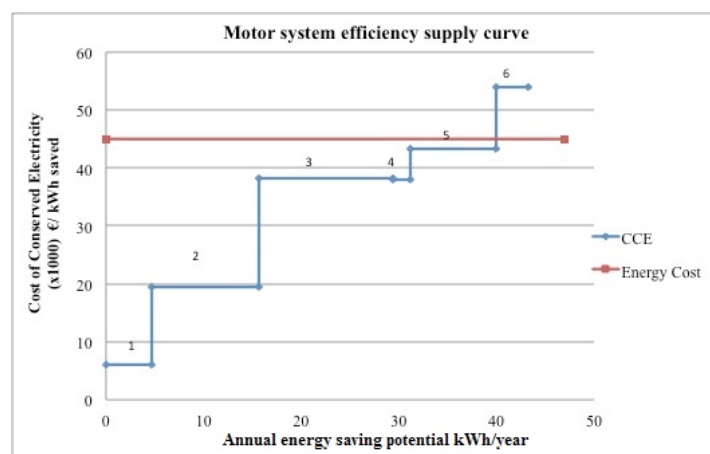


Figure 12. The CSC for the measures proposed for the case under study.

Table 6. Cumulative annual electricity saving by proposed measures.

| No. | Energy Efficiency Measure | Energy Recovery (%) | Cumulative Annual Energy Saving (kWh/year) | Final CCE (€/kWh-Saved) |
|-----|--|---------------------|--|-------------------------|
| 1 | Upgrade system maintenance—fixing leaks and damaged seals | 2.0 | 4696 | 6056 |
| 2 | Upgrade system maintenance—Removing mixer sediments | 5.0 | 15,668 | 19,350 |
| 3 | Hardware improvement—Further motor replacement with a more efficient one | 7.0 | 29,413 | 38,158 |
| 4 | Hardware improvement—Use of new belts | 1.0 | 31,240 | 38,098 |
| 5 | Maintenance advancement—Initiate a predictive maintenance program | 7.0 | 39,917 | 43,214 |
| 6 | Hardware improvement—Use of an inverter | 2.0 | 43,189 | 53,888 |

The horizontal line in Figure 12 represents the energy cost line. The efficiency measures that fall below the energy cost line are both technically feasible and economically feasible, while those falling above the line are technically feasible, but not cost effective.

Therefore, in this study, measure 6, entailing the use of an inverter, is technically possible, but it is not economic or convenient [21]. The motor consumption can be instead managed minimizing the peaks during the startup or the stop of the equipment (Measure 6a), e.g., starting the motor one time a day, and turning off the motor only at the end of the daily work. This means that the motor could have a single peak of consumption (400 A) per day, for 5 s.

In 2012, some of the measures indicated in Table 5 were undertaken: the substitution of the motor after the failure, with a more efficient one (Measure 3), and the consequent use of new belts with high transition power and maintenance free (Measure 4). Those measures brought the motor to reach the high level base case scenario. The CSC was thus recalculated according to the new hypothesis.

Table 6 shows the effect of the measures proposed with the cumulative annual electricity saving and the final CCE for the electric motor system.

As shown in Figure 13, results demonstrated that even only through maintenance optimization—as upgrading the maintenance of the equipment and initiating a predictive maintenance program—it is possible to increase the performance of the system by up to 10%, for a medium base case scenario.

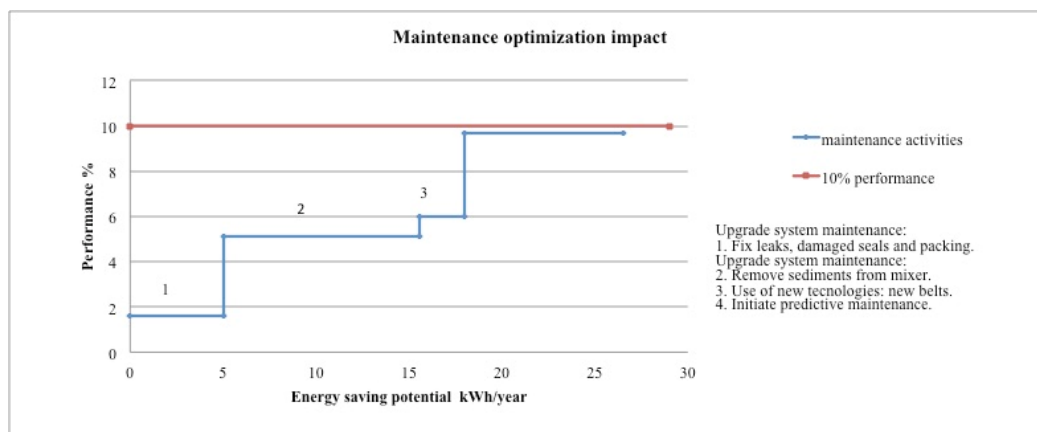


Figure 13. Maintenance optimization impact (case study).

5. Conclusions

When considering the importance of energy saving in industries, this work aimed at developing a model for energy efficiency analysis that is able to support decisions making in industrial process plants.

The methodology allows for presenting the costs and benefits of the technical and operational measures that could be implemented in energy intensive systems for the energy efficiency. With respect to literature models, the proposed one makes explicit the influence of maintenance operations and operational optimization.

The results demonstrated, that even only through maintenance optimization, the recovery could account for the 10% of the total for a medium base case scenarios electric motor system.

Furthermore, based on analysis of historical data, expert inputs and analysis of the economic impacts (balanced cost), the efficiency measures and solutions to achieve higher efficiency of the motor systems were determined.

The implementation of energy saving measures for the case study was based on both technical and economic feasibilities. On the other hand, for industrial application, some limitations have to be acknowledged: some difficulties in obtaining the historical data required for the evaluation and the

presence of multiple factors that could affect the analysis—like productivity—that should be at least qualitatively considered.

However, thanks to the cooperation with the company, the analysis and the results were validated by the experts of the system. These results were compared with the results obtained using traditional method of energy balance sheet, and similar outcomes were confirmed [21].

In the end, it has to be notices that the proposed methodology constitutes a good screening tool to present energy efficiency measures and to capture the potentials for improvement and a base to develop the tools for prognostic and health management systems in process industries.

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Author Contributions: Gabriele Baldissone and Micaela Demichela conceived the need and the potential methodological solution for the industrial domain and designed the framework; Behnoush Darabnia collected the field data and expert knowledge; Gabriele Baldissone, Micaela Demichela and Behnoush Darabnia analyzed the data and developed the analysis tools; Gabriele Baldissone and Micaela Demichela wrote the paper.

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

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