International Journal of Energy Economics and Policy

ISSN: 2146-4553

available at http: www.econjournals.com

International Journal of Energy Economics and Policy, 2021, 11(5), 204-210.

Methodological Approach to Improve Energy Efficiency by Concentrating Operation Points an Electrical Transformer Maintenance Company

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Received: 26 February 2021 **Accepted:** 28 May 2021 **DOI:** https://doi.org/10.32479/ijeep.11333

ABSTRACT

In recent years, companies have developed strategies to improve the environment through the efficient use of their energy resources (Rodríguez Toscano et al., 2019). This practice has been widely used in the goods manufacturing and transformation industry, but many opportunities for improvement remain in the services sector. In this context, this study offers a methodological and analytical approach to improve energy efficiency at a company that provides electric transformer maintenance services, based on performance of energy planning, analysis of concentration of operation points, and the implementation of operational and technological improvements to the processes. The results display total energy savings of 7% after implementation of the operational and technological improvements on only 23% of the company's energy-intensive equipment.

Keywords: Energy Efficiency, Technological Improvement, Electrical Transformers
JEL Classifications: I, L8

1. INTRODUCTION

Services are currently one of the fastest growing and most dynamic economic sectors, comprised mainly of companies that provide services (Lin and Zhang, 2017; UPME, 2017). Many countries consider companies of this type to be key drivers for the development and implementation of policies and strategies related to energy efficiency (Lin and Zhang, 2017; UPME, 2017; Sinceo, 2019).

Numerous studies worldwide have been carried out on energy efficiency in this sector, reporting excellent results (Kangas et al., 2018; Zografakis et al., 2011; Rodríguez Toscano et al., 2019); however, the specialized literature does not report energy efficiency improvements at companies whose main business is equipment maintenance and repair services.

In Colombia, these companies have a major role in the economy and in terms of energy consumption (UPME, 2017; Unidad de Planeación Minero Energética, 2010). Close to 60% of GDP is accounted for by companies directly associated with services sector, and they consume close to 66.4% of total energy (Unidad de Planeación Minero Energetica, 2010). Despite this, energy efficiency management is still incipient at these companies, and in the country in general (ACEEE, 2019; UPME, 2017). The only studies found in the specialized literature cover the services industry, but they do not provide details on company-level energy consumption and/or efficiency (UPME, 2017). Consequently, there is uncertainty regarding the rational use of energy and the future trends of companies of this type.

In the Colombian Atlantic Coast region, one of the major issues that affects the community is the poor quality of electric power supply, due to poor maintenance of the equipment associated with electricity distribution services (Camara de Comercio, 2019; Semana, 2015). The government and the district promote solutions to this issue, and it is expected that soon there will be substantial growth in companies that provide equipment maintenance and repair services for the electric power service industry. In Barranquilla, there has been substantial growth in the companies devoted to the repair and maintenance of equipment and machinery associated with electricity (Camara de Comercio, 2019); however, few of these companies have effective processes in place related to the development of energy efficiency plans (UPME, 2017). This leads to uncertainty regarding their future growth.

Due to this above, this study focuses on the development and analysis of energy indicators using different statistical analysis tools that will provide effective guidance for rational energy use in the context of the operating dynamics of companies devoted to the repair and maintenance of electrical equipment in the city of Barranquilla.

2. MATERIALS AND METHODS

This study presents an energy diagnosis and the implementation of different strategies based on energy planning at a company devoted to the maintenance of electrical transformers located in the city of Barranquilla. The aim is to identify and assess the energy performance indicators that characterize before and after operating dynamics and variability in production (number of repaired transformers) in connection with significant energy usage (electricity) at a services company devoted to the repair and maintenance of low and medium voltage electrical transformers. Figure 1 displays the methodological approach that was used.

The energy performance indicators and the energy baseline were identified and implemented using the guidelines established in the ISO 50001 and ISO 50006 standards (ISO, 2014; 2011). Additional statistical tools were used (dendrogram and Pareto diagram) to determine the main activities and points that characterize the company's normal operational dynamics.

The measurement equipment used for the electric energy load and consumption census was an electric network analyzer, over a 42-month measurement period. The equipment used to determine the technical criteria (temperature, humidity, pressure drops) included a hygrothermograph, a thermographic camera and a luxometer.

2.1. Energy Baseline (EnB)

The energy baseline is established by means of a linear regression of electricity consumption with one or more variables that affect its dynamics over a given baseline time period (ISO, 2011; Cabello Eras et al., 2016). For this study, it was calculated based on monthly electricity consumption and the number of repaired transformers (NRT) for a given class of transformers. These account for practically 99% of all the products it repairs, given that its business focuses on low-voltage transformers.

$$EnB=m \cdot NRT+E_0 \quad (1)$$

m = Electric energy consumption associated with the NRT.
E_0=Electric energy consumption not associated to the NRT.

2.2. Energy Consumption Index (CI)

The energy consumption index expresses the relationship between electricity consumption and the NRT. It is used for the effects of increasing energy efficiency through planning of repairs (NRT) and to determine the existence of any failures or inefficiencies in the process (Grimaldo Guerrero et al., 2018; ISO, 2011).

$$CI = m + \frac{E_0}{NRT} \quad (2)$$

2.3. Pareto as a Tool to Prioritize the Improvements to be Made at Operating Points Based on the Consumption Baseline

In the specialized literature, certain areas of the baseline display greater density or concentration of operating points, due to their production activities and their energy consumption ranges, i.e. the points with highest levels of operation are not uniformly distributed. This leads to uncertainty about the effectiveness of actions intended to improve a company's energy efficiency (Rodríguez Toscano et al., 2020). Additionally, the implementation of actions to improve energy efficiency can be fruitless or ineffective if priorities are not established based on the operation's dynamics.

In order to identify the points of greatest concentration of operations, either by production and/or electricity consumption, a Pareto diagram was developed for both variables. In the case of production, the region indicates that 80% of the operating points are concentrated in 20% of the production range. The region determined by the production Pareto chart is drawn vertically over the consumption baseline. In the case of electricity consumption, the region indicates that 80% of the operating points are concentrated in 20% of the electricity consumption range. The region determined by the electricity consumption Pareto chart is drawn horizontally over the consumption baseline.

The intersection of these two regions indicates the points to be prioritized. If the points in this region are below the consumption baseline, it means that in general the efforts made have produced good results and have a substantial effect on normal operating dynamics, while points above the baseline indicate a contrary effect. When these regions are far away from the general intersection region, it indicates a low level of overall efficiency, because these operating points are the ones that characterize the company's typical operating dynamics.

This tool developed over the consumption baseline enables focusing efforts on the effective implementation and control of energy efficiency and helps identify typical variables that have a significant effect on energy consumption.

2.4. Dendrogram as a Tool to Visualize Distances and Disorder in the Consumption Baseline

The dendrogram measures the Euclidian distance of the operating points that are nearest to the baseline, in accordance with the months of operation, to visualize the disorder and its association to space and time. This enables a quick assessment of the relative energy efficiency at each point.

2.5. Maintenance of Electric Transformers

Electric transformers are a key component for a company's development and productivity because they are the energy source that is easiest to transport. When their maintenance is not adequately planned and implemented, their useful lives decrease and energy waste increases (Metwally, 2011).

With adequate maintenance, power transformers can remain in operation for up to 60 years (Wang et al., 2002). However, certain critical transformer elements degrade over time, such as the taps, core, insulation (oil and paper) and the tank (Murugan and Ramasamy, 2019). A maintenance plan also includes preventive measures to slow down wear of the transformer's components. Preventive transformer maintenance is based on diagnostic testing.

Figure 2 displays the overall maintenance process for electric transformers. It is based, firstly, on a good visual inspection and verification of the overall conditions of the transformer.

3. RESULTS AND DISCUSSION

The following are the detailed results of this study based on the methodology applied.

3.1. Energy Diagnosis

The only energy source used by this company is electricity. Using an electric network analyzer, the following equipment and systems that consume most electric energy at the company were identified. An energy audit was carried out to determine a load census, to analyze and determine electric energy usage, including the distribution of energy consumption at the company's facilities and the average load of each equipment unit.

Figure 3 displays the Pareto diagram used to assess the equipment that most consume electricity at the company.

20% of the equipment account for 80% of electricity consumption, namely:
1. Electric motors
2. Air conditioning system
3. Lighting system.

As expected, given that the company's main activities and procedures consist in rewinding and transporting the transformers at its facilities, electric motors have the highest share of overall electricity consumption, although air conditioning systems also have a high share. The excessive consumption of electricity by

Figure 1: Methodology implemented for the study

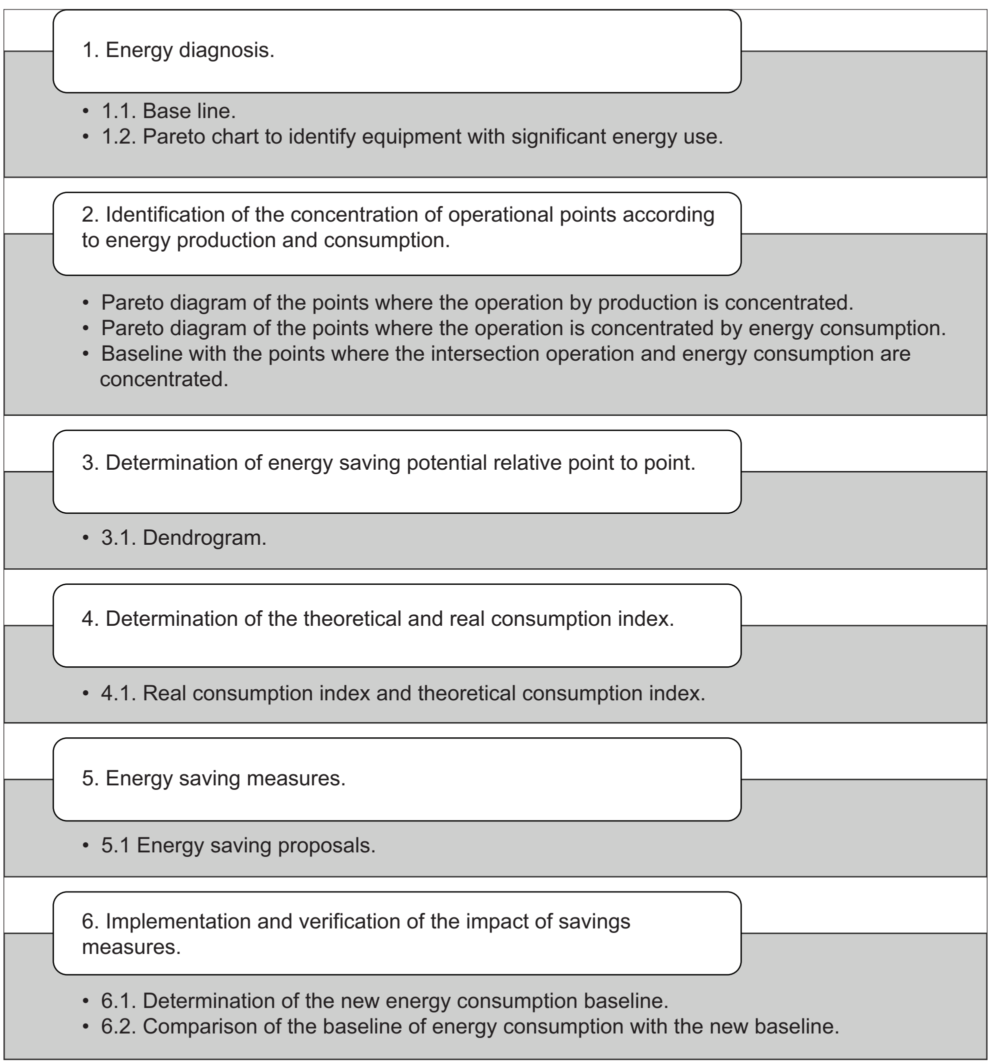
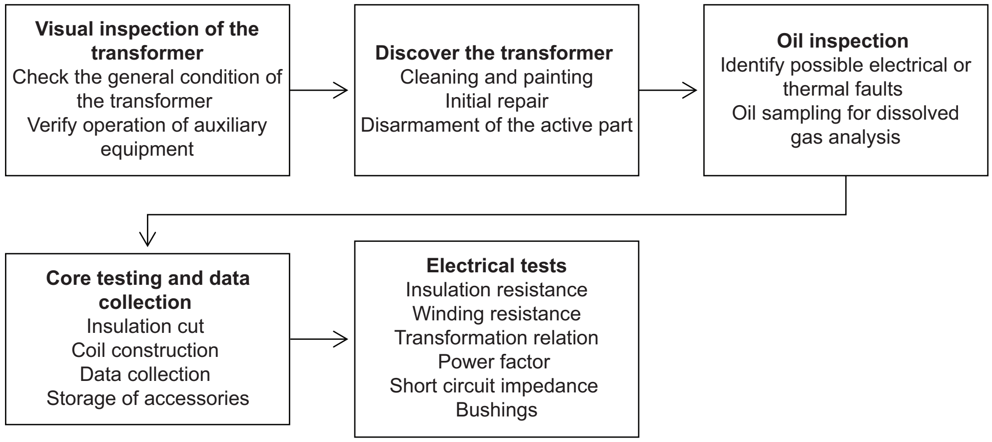


Figure 2: General transformer maintenance process



the air conditioning system is produced by a high level of water condensation, the low set point temperature (17°C), as well as no insulation for several components and insufficient maintenance. Consequently, adequate, and ongoing maintenance of this equipment is required to maintain them in good working order and to avoid over-consumption of electricity.

Figure 4 indicates that the consumption baseline has a high determination level, which indicates a high level of correlation between the variability of energy consumption and the NRT. It indicates that 33.33 % of the operating points are above the EnB. The slope of the EnB indicates that each NRT unit consumes 50.747 kWh of electricity. On the other hand, the intercept on the EnB indicates that electric energy not associated to the NRT is 746.55 kWh. This energy that is not associated with the NRT could be produced by insufficient maintenance and improper usage of high-consumption equipment, but further measurement, statistical analysis and information would be required to ascertain this.

3.2. Concentration of Operating Points in Terms of Production and Energy Consumption

Figure 5 displays the number of operating points in terms of NRT ranges. In Figure 5, the ranges with the greatest number of points are: 32.9-38 and 15-27.6 NRT. Most of the company's activities are concentrated in these ranges, and it is highly likely that these ranges will account for almost all the company's energy consumption. However, it is not possible to visualize the effects without analyzing energy consumption at these points, because there may be operational situations or points that consume a disproportionate amount of energy.

Figure 6 displays the Pareto diagram of the operating points in terms of energy consumption. The ranges with the greatest number of points are: 2099-2444.2 and 2615.9-2789.4 kWh. To enable the analysis of the Pareto diagrams described in Figures 4 and 5, they are superimposed on the energy consumption baseline.

Figure 7 displays the ranges determined in the previous Pareto diagram on the energy consumption baseline. Considering the

Figure 3: Pareto diagram on energy consumption by the company's equipment

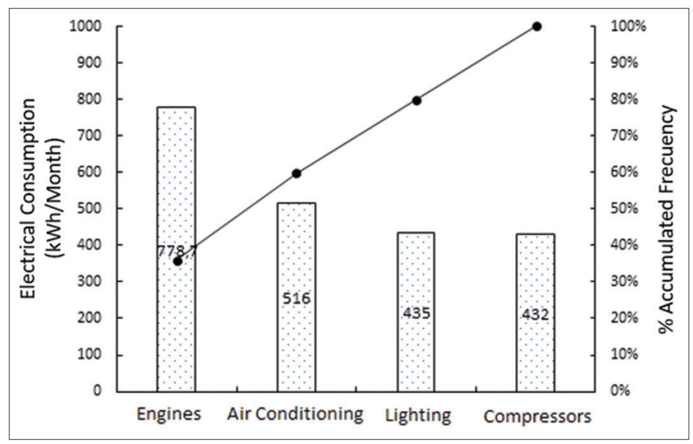
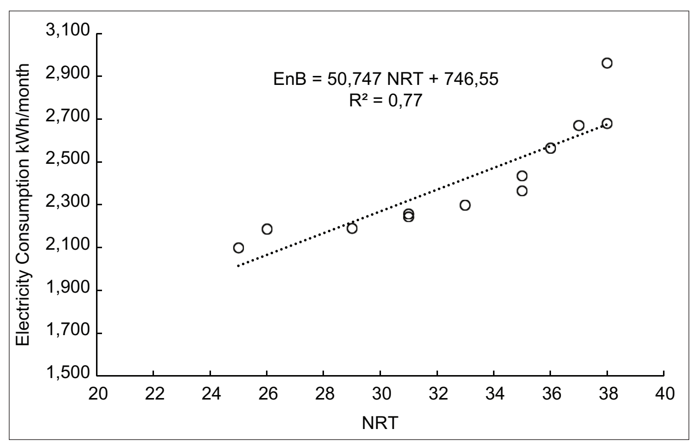


Figure 4: Electric energy baseline (EnB)



intercept ranges and the points that lie above the baseline, we conclude that the savings activities should focus primarily on the points or situations that are within or above the B y C area.

3.3. Determining Potential Relative Energy Savings Point by Point

Figure 8 displays the dendrogram prepared based on the energy baseline. It displays a large difference in operating performance between the August-October group and the month of June (these months are the closest ones and have similar production levels). In this sense, the dendrogram enables viewing significant changes in operations over time, which facilitates the search of atypical values and comparisons in the operation. In June, production and maintenance activities must be reinforced to improve the company's energy efficiency.

3.4. Determining the Theoretical and Actual Consumption Index

Figure 9 indicates that 5 operating points display impairment compared to the theoretical consumption index. This energy performance index shows that the level of performance is low and that deficiencies are caused by variables or factors that are independent from the NRT. The theoretical CI indicates that at a higher NRT, energy consumption per NRT should decrease, which is consistent with the actual results. However, there are atypical operating cases and inadequate performance levels after 37 NRT. The employees attribute this behavior to disorganization and low capacity of control when many transformers must be repaired simultaneously with other repairs.

3.5. Electric Energy Savings Measures

Tables 1-3 display the status of the systems, the savings measures implemented, the benefits and impacts found in the energy audit

Figure 5: Pareto diagram of operating points in terms of NTR

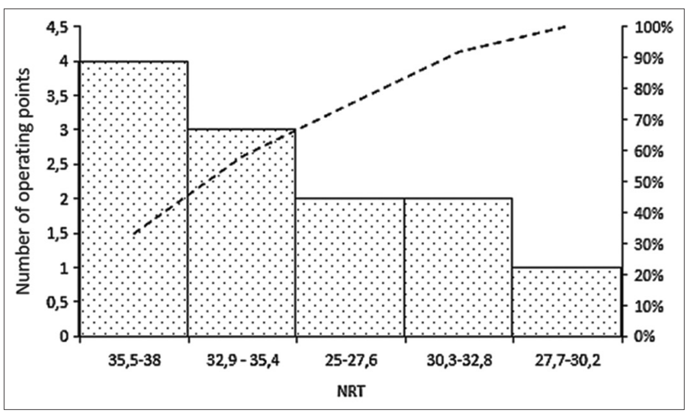
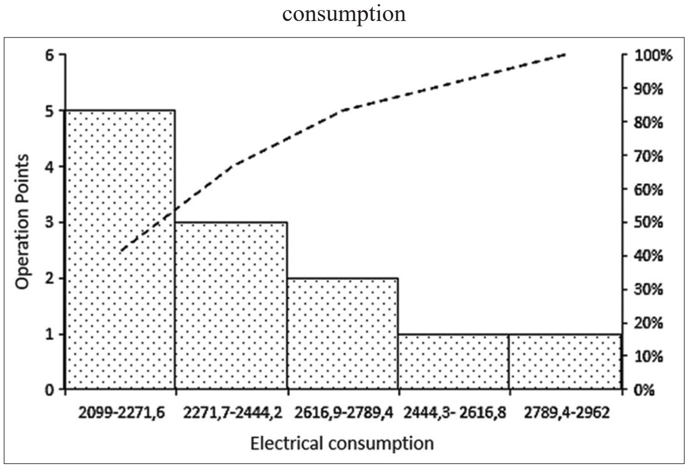


Figure 6: Pareto of operating points in terms of electricity consumption



following the implementation of the saving measures. They display the improvements, the benefits obtained and their impact.

The improvement proposals were well received by the area provisionally responsible for implementing the energy management system (EMS).

Forms will be designed to monitor and record the variables in real time at each machine involved in the process, among other improvements to be implemented.

Table 1: Electric energy savings measures for electric motors

System	Current situation	Savings measures	Benefits	Impact
Engines	Poor lubrication and lack of lubrication record	Increase the frequency of lubrication and keep track of your maintenance and the lubrication system	Energy reduction due to friction losses and increase in the useful life of electric motors	Improved performance in the process and its times. Economic savings by reducing friction losses
	Noise, vibrations, wear on the shafts, heating on the shafts	Bearing replacement and lubrication		
	Inefficient use of motors	Turn off equipment when not in use for more than a minute	Energy savings due to non-use	Economic savings by not using electrical energy

Table 2: Electric energy savings measures for the air conditioning system

System	Current situation	Savings measures	Benefits	Impact
Air-conditioning system	High electricity consumption compared to other venues. 18°C set point	Increase the set point temperature two degrees	Saving the electricity bill	Cost savings in electricity consumption, reduction of water vapor that condenses. Reduces the carbon footprint due to the efficient use of energy
	Excessive condensation of water vapor occurs in systems	Insulate walls, windows, and copper pipes of the HVAC system. Change the closing system of office doors and work areas to avoid the entry of hot air		

Table 3: Electric energy savings measures for the lighting system

System	Current situation	Savings measures	Benefits	Impact
Illumination	Use of bulbs and lamps with high electricity consumption	Use of bulbs and lamps with high electricity consumption	Lighting electrical energy saving of about 60%. Elimination of electrical faults	Improvement in the performance of workers, reduction in electricity consumption, increase in the useful life of systems associated with lighting
	Flashing lighting	Change of wiring and maintenance to the electrical network		
	Poor placement and spacing of fixtures	Relocation of luminaire installation points		

Figure 7: Intersection of points of high concentration of operations and of energy consumption

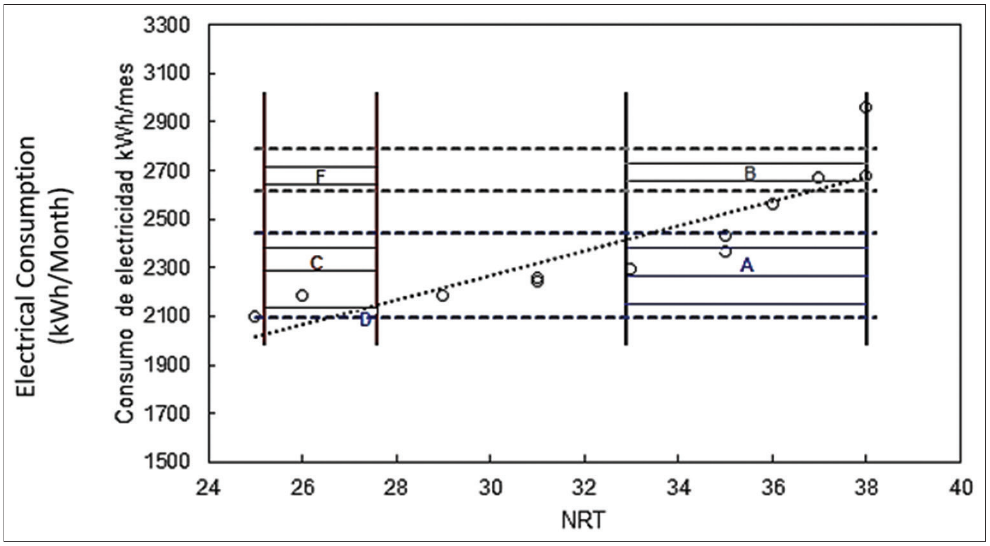


Figure 8: Dendrogram

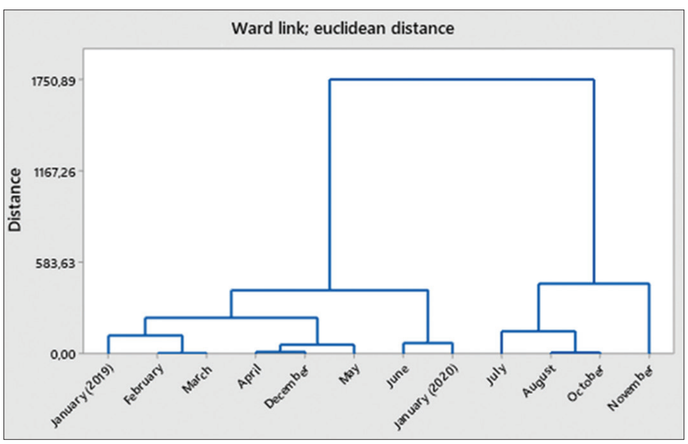


Figure 10: New electricity consumption baseline (EnB)

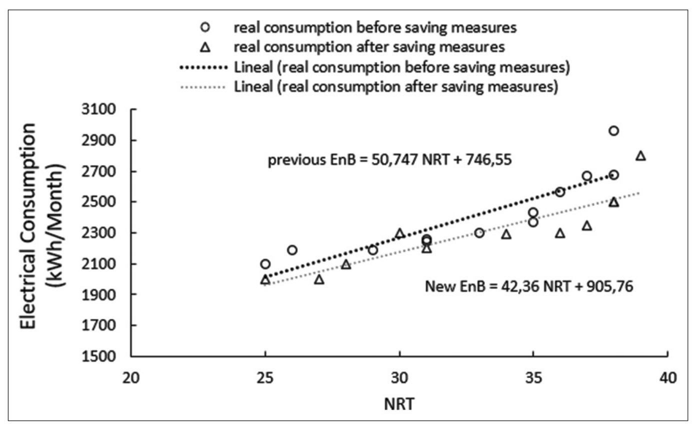
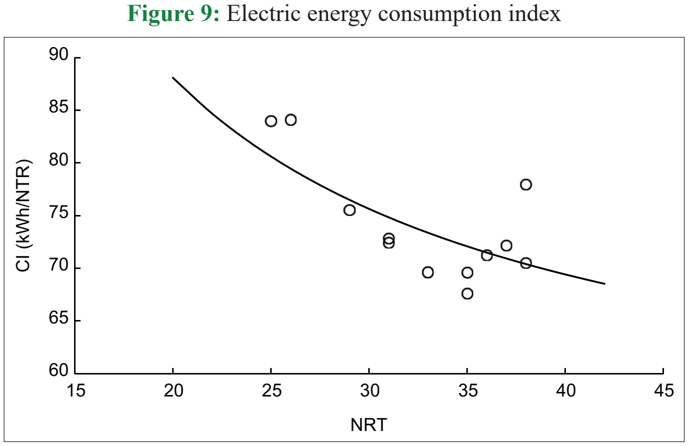


Figure 9: Electric energy consumption index



3.6. Implementation and Verification of the Impact of the Savings Measures

Figure 10 indicates that the slope of the new EnB decreased by 8.387 kWh/NRT compared to the previous EnB, and that 80% of the operating points are lower compared to the previous condition. This demonstrates the effectiveness of the electric energy savings measures compared to the consumption trends of the baseline period. Under the new conditions, energy savings may range between 5% and 16 % depending on production, and total energy savings after implementing the improvements are approximately 7%. These electricity savings were substantial, considering that the strategies were only implemented at 23% of the high electric energy consumption equipment, and that the only savings measures implemented were those that did not require new investments.

The consumption of electric energy that is not associated with production (NTR) increased by 159.21 kWh. This increase was expected, because priority was assigned to maintenance of machines and instruments that are critical for operations to reduce efforts and costs.

4. CONCLUSION

The energy savings measures are effective for the effects of reducing consumption in service companies of this type. The slope of the company's new EnB and operating points decreased, though it should be noted that the energy not associated with the NRT increased. Total electricity savings were approximately 7%, based on the implementation of 33% of improvements. Lastly, most of the improvements do not involve significant costs because most of the required materials and equipment were available at the company.

The methodology assigned priority to the equipment with highest electricity consumption, based on normal operating dynamics. Electric energy consumption in the operations range displayed significant savings and an improved trend line. At the studied company, electric energy consumption was primarily concentrated in electric motors, followed by air conditioning systems and the lighting systems. Regarding the motors, it is important to monitor lubrication and the conditions of bearings, which are in continuous motion because they are a key component in the process of repairing and maintaining electric transformers.

5. ACKNOWLEDGMENTS

The authors thank the Department of Energy of the Universidad de la Costa and the Department of Productivity and Innovation (Intensive Scientific and Collaborative Production Days - CONV-14 2020) of the Universidad de la Costa, Energía Óptima SAS for financing the project, as well as thanks to the student Andrés Mauricio Noguera Silvera, a member of the Newton research seedbed of the Universidad de la Costa for his technical contributions.

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