Factors Affecting the Electricity Consumption and Productivity of the Lead Acid Battery Formation Process. The Case of a Battery Plant in Colombia

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ABSTRACT

This study identifies the main factors affecting the electricity efficiency and productivity of the lead acid battery formation process. A representative sample of 12,286 battery formation processes, developed between June 2014 and June 2015, were used in a statistic analysis. As a result, an energy performance indicator was developed to assess the electricity consumption of battery formation. Given that there are several formation circuits in the formation area, an energy performance indicator was developed for each circuit. The influence of the operational practices, operational teams, workings shift starting time and technical condition of the circuits were analyzed. The influence of the operational practices and the technical conditions of the formation circuits were identified as the main factors affecting the productivity and the electricity consumption. These factors cause a time waste, affecting productivity between 2% and 5%, and increasing the electricity consumption. As a result it is recommended to improve maintenance and operational practices towards higher productivity and electricity efficiency.

Keywords: Energy Efficiency, Productivity, Training Process, Lead-acid Batteries
JEL Classifications: K32, L94

1. INTRODUCTION

The industrial sector consumes 29% of the global energy demand, which is why it is essencial to improve energy efficiency (EE) (Fawkes et al., 2016). The estimated saving potentials from improving the EE in the industial sector is estimated around 20% of the energy consumption, equivalent to 974 million tonnes of oil equivalent (toe) (Chan and Kantamanen, 2015; Fawkes et al., 2016). There are three fundamental approaches to implement EE in industry (Abdelaziz et al., 2011), namely energy management (EM), introduction of new and more efficient technologies or implementation of automatic control systems. Government policies and regulations can aid to promote these approaches.

EM aims at minimizing the costs and environmental impacts resulting from energy consumption, without affecting the production quality of processes, through a continuous improvement of the energy performance based on controling, monitoring, planning and the developing and implementing actions and strategies towards higher EE standars (Abdelaziz et al., 2011; Bunse et al., 2011; Cabello et al., 2016).

The implementation of EM in industry shows good results in several countries (Block et al., 2006; Gielen and Taylor, 2009; Hens et al., 2016; Palamutcu, 2010; Poscha et al., 2015; Rudberg et al., 2013; Vine, 2005; Weinert et al., 2011). Until 2017, some 22870 ISO 50001 certifications were issued worldwide, only 15 of

them were issued in Colombia. In particular, the chemical industry stands as the fourth industrial sector with more certifications in EM with 888 certifications (ISO, 2019). However, the full potential of EM and EE measures to reduce the energy consumption, improve the economic performance and reduce the environmental impact, is yet to be fully exploited (Bunse et al., 2011; Cagno and Trianni, 2014; Giacone and Mancò, 2012; Ospino, 2014; Weinert et al., 2011).

EE is acknoledged as the most cost-effective approach to address energy consumption and related productivity issues (Montalbano and Nenci, 2018; Porter and Van der Linde, 1995). The implementation of EE measures will reduce the industrial energy demand per unit of product, thus reducing economic costs for the same levels of production and impacting its energy intensity (Gamtessa and Olani, 2018). Productivity is frequently affected by time shortage caused by bottlenecks in either continuos or batch production systems, which delay the process (Cuatrecasas, 2009). The performance of manufacturing systems is evaluted with factors like their productivity and EE, as shown by Bajpai et al. (2018). In this study is assessed the energy structure and the effects of the inactivity events in the production line to develop indicators to measure the EE and productivity of manufacturing systems in series.

Electric batteries have a widespread use to store energy in countless applications. Lead-acid batteries account for most of the market share for rechargeable batteries, both in terms of sales value and MWh of production (May et al., 2018; Miloloža, 2013; Pillot, 2015). In 2016, the worldwide installed capacity of energy storage with lead-acid batteries was 9% (Zhang et al., 2018; Zhu and Chen, 2019). An annual growth of 2-4% of lead-acid battery production is estimated until 2025. Currently, three types of lead-acid batteries are manufactured: Starter batteries (for automotive transport), traction batteries (used in electric vehicles) and stationary batteries (used to store energy in renewable sources application).

It is estimated that the automotive industry will continue the use of 12 V lead-acid batteries, as a source of auxiliary power in hybrid and electric vehicles (Gensch et al., 2018; ITRI Ltd, 2017). The production of lead-acid batteries is an energy intensive process, consuming large amounts of electricity and other energy sources (Pavlov, 2011; Report Buyer Ltd. 2015; Sullivan and Gaines, 2010). The energy consumption per kg of lead-acid battery produced is between 15 and 34 MJ/kg, depending on whether the materials are recycled or virgin (Rydh and Sandén, 2005), battery manufacturing consumes 5.8-8.9 MJ/kg (Sullivan and Gaines, 2010) representing some 30% of the total energy, thus its reduction is very significant.

Battery manufacturing demands significant amounts of heat and electrical energy to transform primary raw materials into battery components and parts. Manufacturing and assembling equipment uses a significant share of the electricity (Jung et al., 2016; Pavlov, 2011; Sullivan and Gaines, 2010). According to Rantik (1999), the main energy carriers in lead-acid battery manufacturing are electricity (4.8 MJ/kg), heat (1.68 MJ/kg) and liquefied petroleum gas (LPG, 1.3 MJ/kg). Most of the electricity is used in battery

manufacturing, mainly during battery formation (i.e., when batteries are charged for the 1st time) (Jung et al., 2016; Sagastume et al., 2018).

This study aims at identifying the factors affecting the EE and productivity of the lead-acid battery formation process in a Colombian battery plant.

2. MATERIALS AND METHODS

2.1. Battery Manufacturing
Battery manufacturing includes three general stages (Dahodwalla and Herat, 2000; Rantik, 1999):

- Cell manufacturing
- Battery assembly
- Battery formation process (Sagastume et al., 2018).

The cells used in batteries are manufactured from lead alloys, by casting lead in book molds or in continuous processes like stamping, extrusion, continuous casting or continuous casting and rolling. (Jung et al., 2016). The main energy carrier of cell manufacturing is heat to melt lead.

Battery cells are covered with a layer of lead oxide paste latter cells are cured in a controlled temperature and humidity environment during 32 h. This process requires heat to cure the lead oxide paste (Jung et al. 2016).

Battery assembling place the different components in a plastic case that is latter sealed and ready to add the electrolyte. Battery assembling mainly consumes electricity and compressed air to operate the equipment (Jung et al. 2016).

2.2. Battery Formation
Battery formation is developed in formation circuits, where batches of batteries are formed simultaneously (Cabello et al., 2018; Jung et al., 2016; Pavlov, 2011). During this process, the paste covering the positive and negative cells undergoes electrochemical transformations when reacting with the sulfuric acid of the electrolyte, which transform the paste into an electrochemically active porous material. This process is essential the battery lifespan and their performance (Cope and Podrazhansky, 1999; Pavlov et al., 2000; Petkova and Pavlov, 2003; Thi, 2009). Battery formation account for 50% of electricity used in process of lead-acid battery manufacturing, accounting for the main consumption of electricity (Jung et al., 2016; Sagastume et al., 2018).

The battery formation units include two main components: the loading table where the batch of batteries to be formed is placed (which includes a cooling system to ensure an adequate temperature during the process), and the power supply system (which ensures that the current and voltage during the process have adequate parameters). During the formation process, the current and voltage vary following a formation regime. Pavlov et al. (2000) and Wong et al. (2008) point out that the intermittent load regime (ILR) is the most used one. There are five parameters (i.e., three voltage levels (VINI, VCI1, VCI2) and two current levels (ICC, ICI)) to control the ILR, that works in two operation

modes: Constant current (CC) and intermittent current (IC) as shown in Figure 1.

In CC mode, the battery is charged with a CC equal to its rated current until the voltage reaches the control value V_{CI1}, after which the state of charge of the battery reaches 97%. Afterwards, the circuit opens to reduce the internal resistance passing to the IC mode. In the IC mode, the battery is charged up to 103% of its charge state of charge with regulated current pulses (I_{CI}) during 30 s, of which 10 s of active supply and 20 s without supply to control the temperature and the release of oxygen and hydrogen (Weighall, 2003; Wong et al., 2008). Battery formation is controlled with a computer that measure the currents, voltages, ampere-hour accumulated in batteries and the electrolyte temperature in real time and save the data. The main control parameter of the process is the cumulative ampere-hour, which depend on the battery size, defines the end of the process when it reaches 103% of the nominal charge state of the battery (Chen et al., 1996).

2.3. EE of the Battery Formation Process

Battery formation uses direct current, and its voltage depends on the number of batteries in a batch. The voltage in the supply line and the ampere-hours accumulated in the batteries can be calculated as (Kiessling, 1992):

$$E_p = N V_{DC} C \qquad (1)$$

Where:
Ep – Electricity used in battery formation (Wh)
N – Number of batteries in a batch
V_{DC} – Voltage in the supply line (V).
C – Battery charge capacity (Ah).

Most of the electricity used in the process is stored in the batteries; the remaining energy is loss due to heating and gas emissions, in the AC/DC rectifier and in the supply line and in the formation circuit. Due to the specific share of battery formation in the electricity consumption of battery manufacturing and on the energy costs, these losses must be controlled and kept to a minimum. The efficiency of battery formation is defined as the ratio between the useful energy accumulated in a batch of batteries and the electricity supplied to the formation circuit, depending on factors

Figure 1: Current and voltage pattern in the intermittent load regime

like the manufacturing technology, operational practices, technical condition of the equipment, effectiveness of the maintenance system, the energy quality, etc. (Kiessling, 1992).

Assessing the EE of battery formation process is challenging, mainly because of the difficulties to accurately measure under real operating conditions the useful energy accumulated in a batch of batteries, the internal losses in batteries and the loss in the supply lines and in the rectifier. However, it is possible to measure or determine the energy consumed in the formation process of each batch of battery which can be used to evaluate the EE of charging ten 1, is rather useless in this case because it refers to the nominal energy demand, the actual energy consumed can be calculated like:

$$E_T = \int_0^{t_1} p(t)\,dt = \int_0^{t_1} V_{DC}(t) \cdot I_{DC}(t)\,dt \qquad (2)$$

Where:
E_T - Electricity consumed during battery formation (Wh).
$p(t)$ - Power (W).
V_{DC} - Voltage in the supply line. (V)
I_{DC} - Current in the supply line. (A)

The trapezium rule (a numerical method) can be used to solve equation 2, and calculate the electricity consumed during the battery formation batches registered in the plant database:

$$E_T = \sum_{i=1}^{n} V_{DCi} \cdot I_{DCi} \cdot t \qquad (3)$$

$$t = \frac{T}{n} \qquad (4)$$

Where:
n - Number of registered values.
V_{DCi} - Voltage registered in the i-est interval (V).
I_{DCi} - Current registered in the i-est interval (A).
t - Interval of time between registers (equation 4).
T - Total time of battery formation (s)

For quality control purposes, the database keeps the data of the formation processes developed in the last 5 years. With this data is possible to determine the electricity consumption in the formation of the battery batches saved in the database and correlate it with the production to develop an EE indicator (EEI) to assess the influence of different parameters on the electricity consumption. The methodology followed takes as a starting point the recommendations of ISO 50004 and 50006 (ISO, 2012; ISO, 2014) to develop EEI in the energy planning stage of an EM System (EMS):
- Evaluation of historical data, regression analysis between energy consumed and battery production to develop an effective EEI.
- Identification of the factors affecting the EE of battery formation.
- Statistical analysis to identify the factors with more influence on the electricity consumption of battery formation.

2.4. Battery Plant

This study was developed in a Colombian battery plant. Between 2012 and 2015 battery production increased from 742,600 to
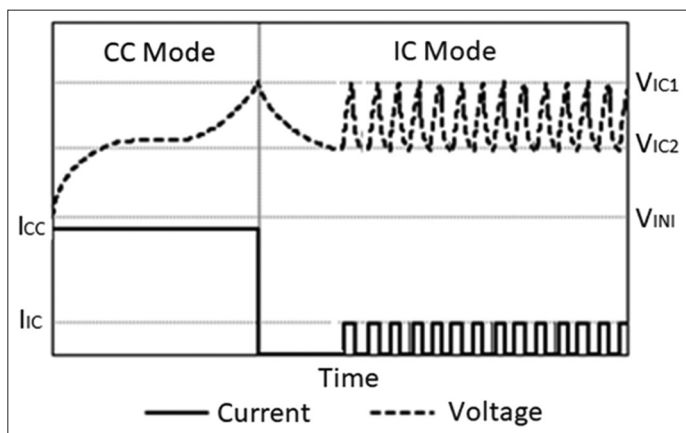
1,110,900 per year (i.e., an annual growing rate of 14%), producing 168 different battery types. Electricity consumption also increased during the same period, thus improving the EE in this case is cornerstone due to the significant costs of energy. In particular, battery formation consumes around 480 MWh per month, which represents over 50% of the total electricity consumption in the plant. In the formation section there are 17 formation tables with 12 formation circuits each. Each circuit is designed to simultaneously form batches of 18 batteries. In total, the batteries are formed in batches of 108 batteries per table using six circuits simultaneously. The supply of electricity is independent for each circuit. An AC/DC rectifier per circuit, with a nominal input of 280 V (AC), 324 V (DC) output and maximum current of 130 A, is used to supply the direct current required in the formation process. Batteries are connected in series as shown in Figure 2 (Sagastume et al., 2018; Cabello et al., 2018).

The process is controlled by a software that establishes the voltage and current values during the process, and save the data in a database. The control parameters are measured at one second intervals. The formation process is developed using an intermittent loading regime (Figure 1). The maximum load to accumulate in the batteries (Ah) depends on the battery model, once this value is reached, the software stop the process.

3. RESULTS AND DISCUSSION

The monthly battery production and the monthly electricity consumption data were used in the general analysis. To assess the parameters influencing the EE of the formation process, data from a random sample of processes developed between July 2014 and July 2015 was used.

Figure 2: Battery charging circuit
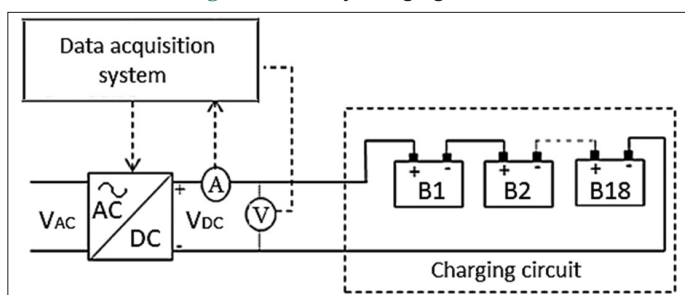
Source: Cabello et al., 2018

3.1. Assessment of Historical Data, Regression Analysis and Development of an Effective EEI

EEI are an important tool to assess and monitor the energy performance of battery formation (Sagastume et al., 2018). Therefore, as a first step to develop an EEI, a correlation analysis was performed between the monthly battery production and the electricity consumption in the plant. The regression analysis result in a correlation of $R^2 = 0.685$, >0.6, so the ratio between the batteries produced and the electricity consumption can be useful to build an EEI (Figure 3a). However, since there are significant differences between the types of batteries manufactured, a second correlation analysis was carried out introducing the concept of equivalent production as recommended in ISO 50006 (Li et al., 2014).

The equivalent battery production (P_{eq}) was determined as:

$$P_{eq} = P\, k_b \tag{5}$$

Where:
P - Monthly production of batteries.
k_b - Coefficient of capacity of the battery type (equation 6).

The factor k_b depends on the electricity consumption required by each battery type to during formation. This factor is calculated as the ratio between the electricity required for the formation of a battery type to the electricity required for the formation of the smallest battery type manufactured in the plant:

$$k_b = \frac{C_b}{C_{bmin}} \tag{6}$$

Where:
C_b - Capacity of the type of batteries analyzed (Ah)
C_{bmin} - Capacity of the smallest type of bacteria that is produced (Ah).

The linear regression analysis between equivalent battery production on monthly basis and the monthly electricity consumption is shown in (Figure 3b), highlighting a significant improvement on the correlation ($R^2 = 0.78$) as compared to Figure 3a.

Based on these results, the correlation analysis is developed to assess the application of an EEI (equation 7), based on the equivalent production, to assess the EE in the battery formation process.

Figure 3: (a and b) Regression analysis between the battery production on monthly basis and the monthly electricity consumption
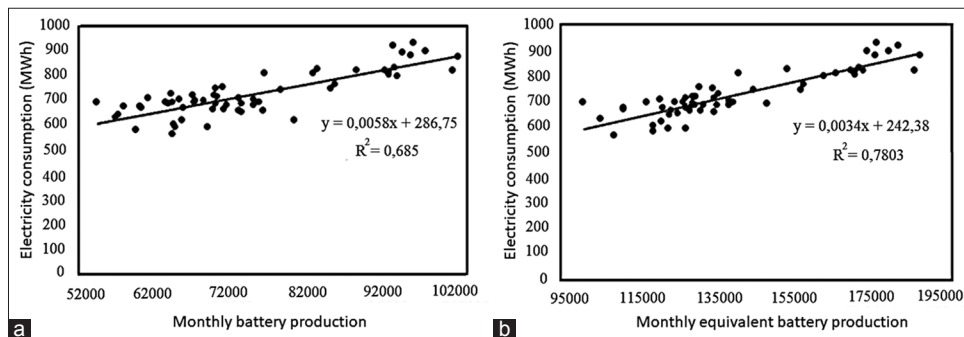
$$EEI = \frac{E_B}{E_{BB}} \qquad (7)$$

Where:

E_B - Energy consumed in the formation of each battery batch (KWh)

E_{BB} - Equivalent batteries in a batch.

The EEI is validated using a regression analysis of the formation process by circuits. Figure 4 shows the correlation between the equivalent production and the electricity consumption of battery formation with a correlation of $R^2 = 0.85$. Therefore, this indicator can be considered as a strong indicator to assess the EE of battery formation.

In each formation process, 6 charging circuits with a batch of 18 batteries operates simultaneously in a table. The control system individually saves the data for each formation circuit and for each table. Currently, a total of 55,000 processes, developed in 204 circuits are available in the database. The influence of the technical condition of the formation circuits is assessed with a sample of the 55,000 processes. The sample size, calculated using equation 8, was of 12,286 for a confidence interval of 95%.

$$n = \frac{k^2 \cdot p \cdot q \cdot N}{\left(e^2 \cdot (N-1)\right) + k^2 \cdot p \cdot q} \qquad (8)$$

Figure 4: Regression analysis between the equivalent battery production and the electricity consumption of battery formation
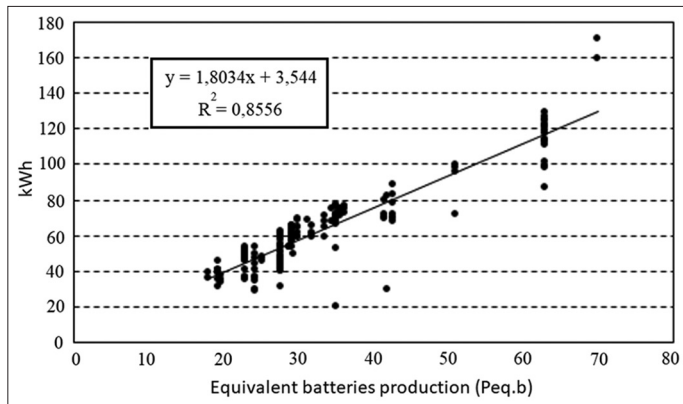

Figure 5 shows the number of formation processes selected per circuit for the process sample. On average, there are some 60 processes selected per circuit.

Since there is a large volume of data from direct measurements of the formation process, it is necessary to evaluate the behavior of the variables to identify outlier values, to exclude them from the sample. Thus, a Hamper filter is implemented as shown in Figure 6. This filter uses the mean absolute deviation (MAD) to identify outliers:

$$DMA = 1.4826 \; median \; \{(Xi - X^*)\} \qquad (9)$$

Where X_i is the data i of the analyzed series and X^* is the median of all the data. Outlier data (i.e., data lower than $\bar{X} - MAD$, or higher than $\bar{X} + MAD$) was filtered. The results of the filtering process of the EEI values used in the training process for each circuit are shown in Figure 6. In total, 68 out-of-range data are identified (2.3% of the sample).

## 3.2. Factors Affecting the EEI of Battery Formation

To define the main factors affecting the energy consumption and efficiency of battery formation, different interviews were developed with the technical staff operating the processes and a group working session. Initially, the factors indicated by Kiessling (1992) were considered. The results were summarized in a fishbone diagram (Figure 7).

3.3. Statistical Analysis of the Technological Factors Affecting the EE of Battery Formation

In this case, the influence of technical conditions and the maintenance on the EE of battery formation is assessed. Initially, it was assessed if there were statistically significant differences between the averages EEI of the data used in the training processes of each circuit. Additionally, it the circuits with the best and poorest energy performance were identified. The mean values were compared with the fisher's significant differences method, using the Statgraphics Centurion XV software. Figure 8 show the results of the analysis.

Results shown with 95% confidence that there are significant differences between the mean value of the EEI of the load circuits,

Figure 5: Formation processes selected per circuit for the process sample
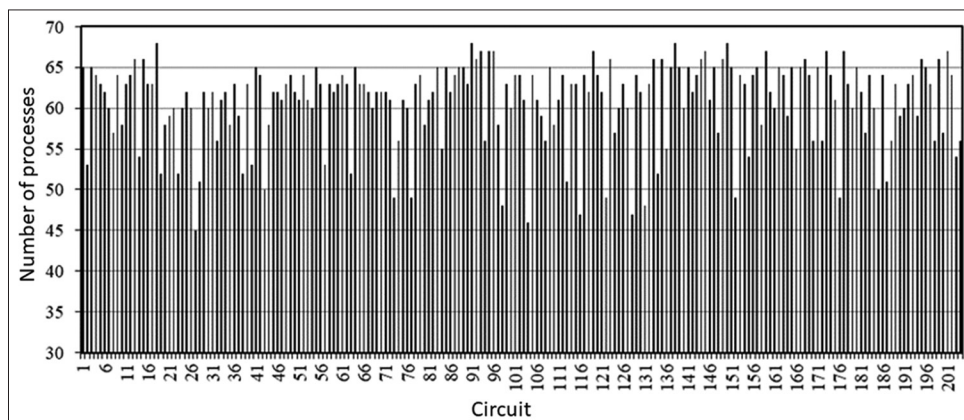
confirming that technological factors influence the EE of battery formation.

In total, three homogenous groups of circuits were identified:
- Circuits with higher EEI
- Circuits with intermediate EEI
- Circuits with lowest EEI.

The performance of the groups of circuits identified were compared in a technical analysis, to identify the causes of their performance, and propose actions to enhance their EEI.

The temperature of the electrolyte during battery formation, which is controlled with the cooling system used in the formation tables and should vary between 54 and 64°C, was also assessed. To this end, a regression analysis of the average temperature of each formation process and their EEI, resulting in low correlation, thus concluding that the electrolyte temperature within the temperature range significantly influence the EE of battery formation. The

limited control of the electrolyte temperature during the process impact the efficiency of battery formation. The malfunctioning of the temperature sensors can also lead to electricity losses during the process.

3.4. Influence of the Electric Power Quality on the EE of Battery Formation

The electric power is supplied through two electric transformers to the battery formation circuits. Each transformer supply different circuits. In this case, the mean value of the EEI of the battery formation processes developed in the circuits supplied with one transformer were compared to the mean value of the circuits supplied by the other transformer. The results show no significant differences between the EEI mean values of formation processes in the circuits supplied by each transformer (Figure 9).

3.5. Analysis of the Influence of Factors Associated with Personnel in the EEI

The staff operating the battery formation process is subjected to specific working conditions, including some risks like the risk of contact with electric sources during the load process, the exposure to harmful gases (i.e., hydrogen, oxygen, sulfuric acid), the risk of explosion in the presence of an ignition source, tripping with cables or objects, etc. This work environment affects the concentration of the staff and their operation. To assess the influence of the staff operating the formation process, two factors were evaluated:
- The teams developing the process
- The starting and ending times of battery formation.

Four teams of five people each develop battery formation processes in the plant. The EEI mean value of the processes developed by each team are compared).

Results show that there are significant statistical differences between the EEI means of the four operational teams, with 95% of confidence.
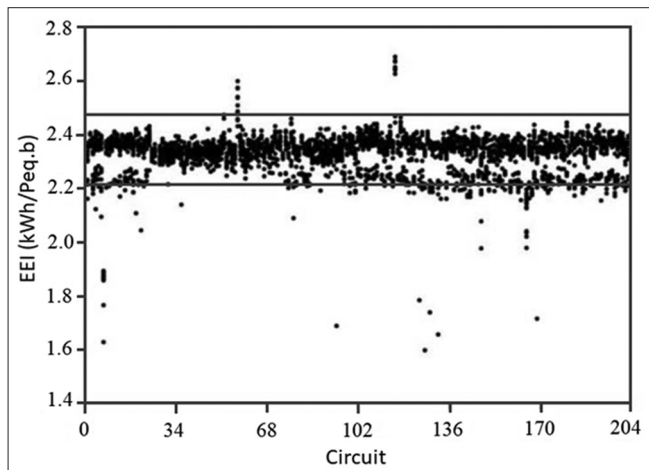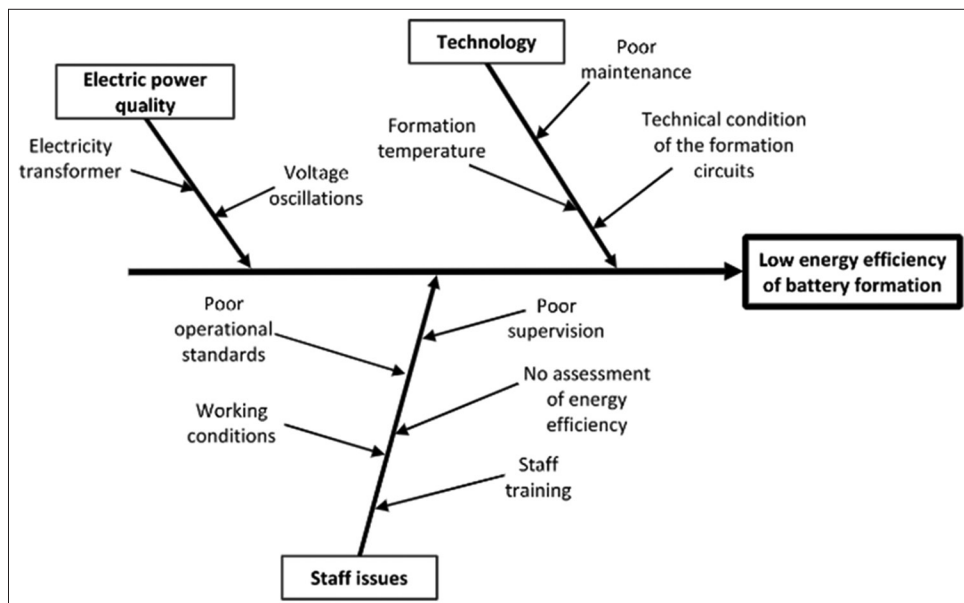
Figure 6: Outlier filtering process

Figure 7: Factors affecting the energy consumption and efficiency of battery formation

Source: Cabello et al., 2018

Figure 8: Statistical analysis of the data used in the training processes of each circuit
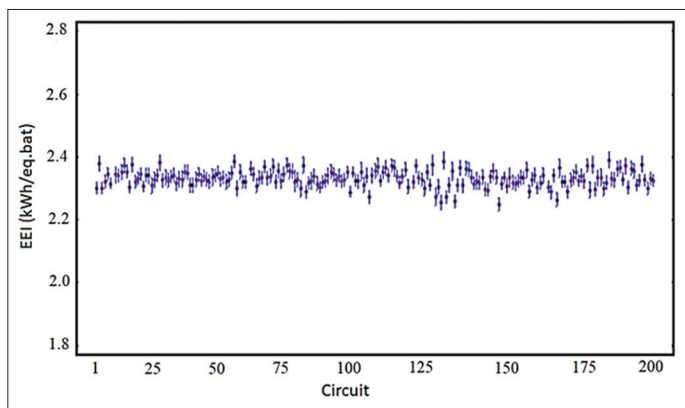

Figure 9: IEE mean of the formation processes developed in circuits supplied by each transformer
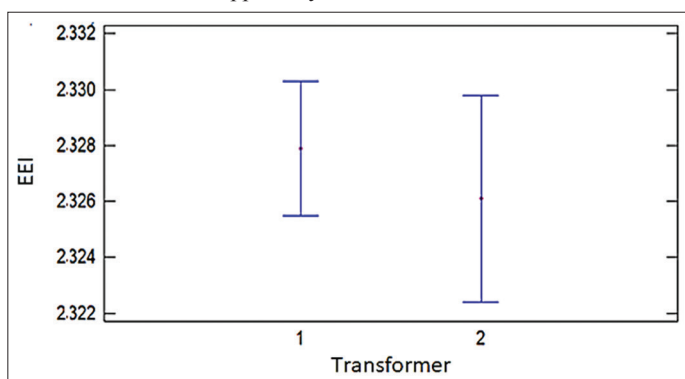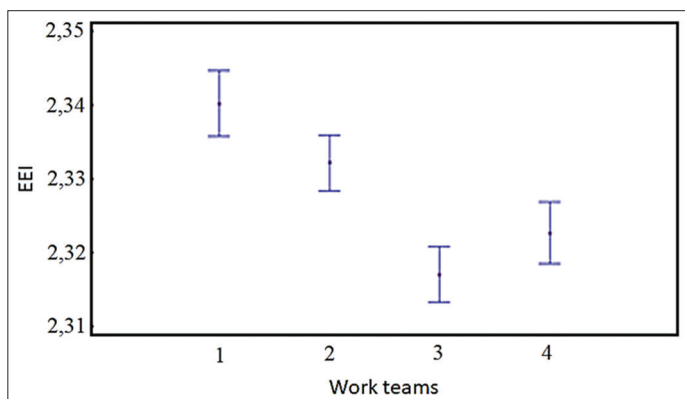

Figure 10: Mean value of the EEI of the battery formation operational teams

Moreover, results in Figure 10 show that there are statistically significant differences between the mean values of the EEI of the formation processes developed by each team, highlighting the better performance of teams 3 and 4 as compared to teams 1 and 2.

The battery formation unit operates 24 h 7 days a week. The operational teams cover 12-h shifts, shifting at 7 a.m. and at 7 p.m. Each operational team includes a supervisor. Since the starting hour of the shift can influence the operational performance of the teams, the EEI mean value was assessed dividing the day in four 6-hour intervals, starting at times:

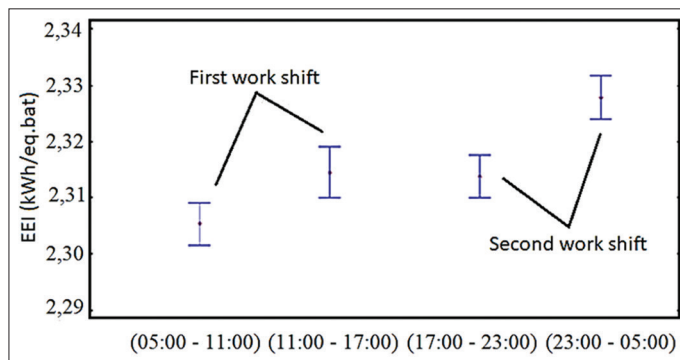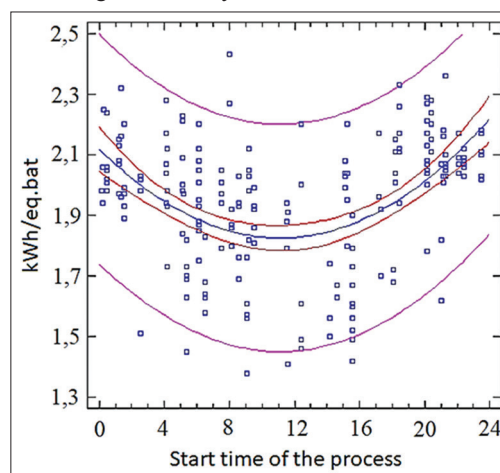**Figure 11:** Mean EEI for the formation process initiated at different times of day

Figure 12: Regression analysis of the EEI and the starting time

Interval 1: between 11:00 p.m. and 5:00 a.m.
Interval 2: between 5:00 a.m. and 11.00 a.m.
Interval 3: between 11.00 a.m. and 5:00 p.m.
Interval 4: between 5:00 p.m. and 11:00 p.m.

Figure 11 shows the results pointing to statistically significant differences in the mean value of the EEI between the formation processes developed as a function of the starting time.

Figure 11 shows that the EEI of the formation processes has statically significant differences, depending on the starting time of the process. A polynomial regression analysis, developed with the Statgraphics software in the different circuits, resulted in a statistically significant relationship between the electricity per equivalent battery (kWh/P_{eq}) and the starting time of the process, with a confidence of 95%. Figure 12 shows the results of the regression analysis, from which the following equation was obtained:

$$Electricity\left(\frac{kWh}{P_{eq}}\right) = 2,118 - 0.0538 \cdot \left(Starting\ time\right)$$
$$+ 0.0023726 \cdot \left(Starting\ time\right)^2 \tag{10}$$

The activities developed by the operational teams, which depends on their preparation, their focus during the activities and the standardization of procedures, significantly influence the EE of battery formation.

3.6. Effects of the Duration of Battery Formation on the EEI and the Productivity

A detailed review of the battery formation data, aids to identify inefficiencies that affect the productive flow, introducing "bottlenecks," and in occasions reduce the battery formation time. The main cause of inefficiencies detected during battery formation are:

• The malfunctioning of the AC/DC rectifier, which causes an inadequate formation current and voltage, thus affecting the electricity consumption during the process
• Malfunctioning of temperature sensors
• Inadequate installation of cables and connectors, which causes higher losses and higher electricity consumption
• Inadequate operational practices of the technical staff operators during the placement of batteries (i.e., inadequate installation of cables and connections on the battery, causing higher heat loss (Sagastume et al., 2018)) in the formation circuits
• Limited supervision of the process, which causes that the battery batch remains connected to the formation circuit, long after the formation process is concluded (Cabello et al., 2018).

Since battery formation ends once the battery, receive the amperes-hour of load capacity defined for its model (Chen et al., 1996; Cabello et al., 2017), the control system of battery formation, set a specific algorithm with different formation times for the different battery models. However, the formation time of the same battery model varies depending on the technical condition of the formation circuit and the operational practices during battery placement in the circuit. This result in some processes forming the same battery model during different time lapses, and the operational staff uses the longest periods as a reference to guarantee that the formation process is completed before the dismantle the battery batch from the formation circuit and ship them to quality control. In practice, the circuits finishing the formation processes more rapidly waste some time before the battery batch is dismantle and a new batch is placed, which affect productivity.

The time wasted between the formation of a battery batch is completed and a new batch is placed on the formation circuit is calculated as:

$$t_{exc} = \sum_{i=1}^{n_c}(t_i - t_{min}) \tag{11}$$

Where:

t_{exc} – Time excess to dismantle a batch of formed batteries and place a new batch of batteries in a formation circuit (min)
t_i - Time to place a new batch of batteries in a circuit (min).
t_{min} - Lowest battery formation time for a specific battery model (min).
n_c - Number of circuits included in the formation process.

The results point to 871,600 min (14,528 h) wasted between the ending of the formation process a batch and the placement of a new batch in the circuit, for the sample assessed. It must be pointed that, inn practice there are several circuits wasting time simultaneously, which result in the significant waste of time identified.

The batteries that could have formed during the time wasted on every circuit, was estimated considering the smallest battery model (that takes 426 min to be formed) and for the biggest battery models (that takes 1,431 min). The batteries that could have formed were calculated as the ratio between the time wasted on a given circuit and the time it takes to form a batch of the battery model considered.

$$B_{nc} = 18 \cdot \frac{\sum N_c \cdot t_{exc}}{t_{load}} \tag{12}$$

Where:

B_{nc} – Batteries that could be charged during t_{exc}
t_{load} – Time it takes to form the battery model.
Nc – Number of circuits wasting time during battery formation.

Results show that some 36,828 batteries of the smallest model and some 10,936 batteries of the biggest model could have formed during the wasted time (i.e., between 2 and 5% of the 2012-battery production, and between 1% and 3% of the 2015 production). The time wasted is mainly the result of inadequate operational practices, and on the other hand, circuits in poor technical conditions that causes delays in the formation process affecting productivity, and additionally affecting the EEI (Sagastume et al., 2018). Addressing these factors can save electricity (Cabello et al., 2018) with measures like:

• Periodic assessment of the technical condition of the formation circuits.
• Define an approach to certify the technical condition of wires and connectors.
• Clean the surface of connectors before placing them in a battery before placing the battery in the formation circuit.
• Improve the maintenance system of the formation circuits to prevent issues on wires and connectors.
• Redesign connectors to facilitate the process of battery placement in formation circuits.
• Control more thoroughly the formation time of batteries according to their model.
• Reduce the working shifts of the operational staff from 12 to 8 h.

4. CONCLUSIONS

The performance of battery formation is strongly dependent on the operational practices implemented and on the technical condition of the formation circuits, which in turn significantly affect both the productivity and the electricity consumption of a battery plant. Developing an adequate maintenance system for the formation circuits, providing a suitable training to the operational staff operating the formation area and guarantying a proper supervision during the working shifts in the formation area is of the essence towards higher productivity and electricity efficiency standards during battery formation.

The issues detected during battery formation accounted for productivity losses of 1-5%, which in turn contributed to higher electricity consumption of battery production in general and of the formation process in particular.

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