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Industrial Decarbonization by a New Energy-Baseline Methodology. Case Study

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Abstract: The main target of climate change policies in the majority of industrialized countries is to reduce energy consumption in their facilities, which would reduce the carbon emissions that are generated. Through this idea, energy management plans are developed, energy reduction targets are established, and energy-efficient technologies are applied to achieve high energy savings, which are environmentally compatible. In order to evaluate the impact of their operations and investments, companies promote measures of performance in their energy management plans. An integral part of measuring energy performance is the establishment of energy baselines applicable to the complete facility that provide a basis for evaluating energy efficiency improvements and incorporating energy performance indicators. The implementation of energy management systems in accordance with the requirements of ISO Standard 50001 is a contribution to the aim and strategies for improving cleaner production in industries. This involves an option for the industry to establish energy benchmarks to evaluate performance, predict energy consumption, and align production with the lowest possible consumption of primary and secondary forms of energy. Ultimately, this goal should lead to the manufacturing of cleaner products that are environmentally friendly, energy efficient, and are in accordance with the global environmental targets of cleaner manufacturing. This paper discusses an alternative for establishing energy baselines for the industrial sector in which several products are produced from a single raw material, and we determined the energy consumption of each product and its impact on the overall efficiency of the industry at the same time. The method is applied to the plastic injection process and the result is an energy baseline (EBL) in accordance with the requirements of ISO 50001, which serves as a reference for determining energy savings. The EBL facilitates a reduction in energy consumption and greenhouse gas emissions in sectors such as plastics, a sector which accounts for 15% of Colombia's manufacturing GDP.

Keywords: energy efficiency; sustainable consumption; ISO standards 50001; standardization

1. Introduction

The growth of industrial activity since 2000 in the countries which are members of the International Energy Agency (IEA) and other major economies, has led to increases in energy use. For 2017, the annual increase in global energy use was estimated to be roughly 2%. However, energy efficiency has prevented further increases in consumption due to efficiency improvements in the industry and service sectors [1–3]. The growth in energy consumption has been largely driven by a long-term trend of increasing production in industrial sub-sectors such as the chemicals, steel, cement, paper, and aluminum sub-sectors [4,5].

In 2017, mandatory policy-driven energy efficiency targets and standards covered less than 25% of total industrial energy use in most regions of Colombia. Many of these standards and targets, focus on minimum energy performance standards for electric motors, while few are mandatory overall performance targets for industrial firms and sectors [4]. Voluntary energy efficiency policies do exist in many regions; for instance, the number of International Organization for Standardization ISO 50001 certifications for industrial energy management systems reached at least 21,500 in 2017, according to a voluntary survey conducted by the ISO [1,6].

The implementation of energy management systems, as well as information, training, and capacity building programs, is encouraged by tax incentives and financing measures [5].

Therefore, energy efficiency associated with cleaner production contributes to sustainable development in industry through efficient management of natural resources, the use of renewable energies, greater efficiency of industrial manufacturing and other strategies, but also contributes to the manufacturing of quality products [7,8].

In South America, the implementation of strategies for cleaner production in industry has been advancing, despite the high costs involved in the processes of implementation [9]. The measures implemented in the industrial sector, and focused on reducing the use of energy in the facilities and associated carbon emissions, are framed within the context of national and international policies and initiatives, which combine the bases for the economic growth of the country to be carried out with sustainable development.

The decarbonization of industrial energy consumption is critical to the mitigation of global climate change, which could present multiple challenges, particularly for regions in the early stages of industrialization that are committed to reducing energy consumption under 2-degree targets [10]. Countries such as the United Kingdom (UK), have launched a transition to a low-carbon economy and society, by aiming to reduce their "greenhouse gas" (GHG) emissions and decarbonization, while improving productivity and creating employment opportunities [11].

To achieve this, policies implemented by the Colombian government have promoted strategies and measures in favor of energy efficiency. Energy policies such as PROURE [12] and Directive 1715 [13] have been implemented to promote the growth of renewable energies and foster the efficient management of energy, in search of favoring the reduction of consumption and diversifying the current energy generation of Colombia. All of these measures are alternatives that are in line with the cleaner production objectives implemented by industry.

The ISO Standard 50001 was established at the international level to help the industrial sector to implement the systems and processes necessary for energy performance improvement, including energy efficiency, energy use, and consumption [14,15]. Its implementation is focused on the reduction of greenhouse gas emissions, energy costs, and other related environmental impacts. These are the primary targets for achieving cleaner production in the industrial sector [8,14,16]. It is estimated that the standard, as applied to different economic sectors, could influence savings of up to 60% in worldwide energy consumption [17,18]. Reducing energy consumption is essential for countries to achieve their national and international GHG reduction commitments [19].

Recent studies show advances in the use of technology to contribute to the decarbonization of both the industrial and service sectors, regarding indoor air quality in places such as schools, offices, and public institutions [20,21].

The current research guidelines focus on studies related to energy management performance, based on the ISO Standard 50001. The development of the ISO Standard 50001 and energy management have attracted the attention of senior management of industry towards implementing continuous improvement processes, as stated by Kanneganti et al. [22]. Regarding the implementation of the standard's guidelines, Pelser et al. [23] developed and implemented an energy performance report covering the verification of ISO Standard 50001, in a South African cement plant where the cost of electricity was reduced by 25%. This research confirms that from a quality-point of view, this ISO Standard 50001 management system ISO Standardenables monitoring of the energy performance of equipment and continuous improvement of operations. Bonacina et al. [24] showed the state of implementation of certifications in Italy. The overall picture shows that Italy, one of the leading countries in energy efficiency policy development, has suffered a significant delay in the implementation of Energy Management System (EnMS) by industry.

Jovanović et al. [25] studied the implementation of ISO Standard 50001 in 52 companies in the priority industrial sectors in Serbia and established the level of company compliance for each stage of the standard. The overall compliance level is 59.05%. The results of this research provided scientific data to help improve national policy and education on energy management in the country. Benedetti et al. [26] discusses a methodology for energy performance management through the development, analysis, and maintenance of Key Energy Indicators in manufacturing plants, while taking into account the requirements of ISO 50001 and ISO 50006. The proposed methodology allows for immediate identification of energy yield deviations from the manufacturing plant through the monitoring of Key Energy Indicators over time, and the identification of the potential causes of any deviation.

Therefore, it is clear how the implementation of energy management systems aligned to the requirements of ISO Standard 50001 constitutes a contribution to the aims and strategies of improving cleaner production in industry. Thus, in this case, an alternative is proposed to establish energy baselines for industry, in which several products are produced through a single raw material, while the baseline determines the energy expenditure of each product and its impact on the overall efficiency of industry.

The Energy Baseline is a benchmark that characterizes and quantifies the energy performance of an organization over a specified period of time. The energy baseline allows an organization to evaluate changes in energy performance between selected periods, and it is also used for the calculation of energy savings, as a reference before and after the implementation of actions to improve energy performance [27,28].

However, if a baseline is not established correctly, then the wrong data could be obtained for Key Energy Indicators, energy saving potentials, and energy budgets. Thus, an adequate energy baseline approach requires comparing the energy performance of a piece of equipment, process, plant, or enterprise, in relation to the levels of the production variable [29].

Consequently, it is necessary to establish an appropriate methodology to calculate the energy baseline adequately and to develop new methodologies for readjustment or standardization. This implies finding industries where several products can be made at the same location, each with its own energy intensity factor. Thus, the necessity arises to establish comparisons between different facilities using Key Energy Indicators, without taking into account the variables that affect energy performance. This means relating specific energy consumption to the production rate when, for instance, there is a base level of energy consumption while production capacity fluctuates. In industries whose aim is to process raw materials into manufactured products, energy consumption is proportionally associated with production levels. Therefore, energy performance can be assessed through an energy baseline modeled from a linear regression analysis, that is established using historical data on energy consumption and the production variable in each case. [30,31]. The implementation of the methodology introduced above to establish baselines in the industry, complemented by non-parametric frontier analysis, provides an overall analysis of the scope for improving energy efficiency. In this case, it focuses on a sector with high energy consumption, which is the plastics industry [32]. Therefore, this study is relevant in order to establish the fulfillment of energy targets defined in Colombia.

2. Materials and Methods

Research on the Colombian plastic industry is based on the analysis of production models whereby, in most cases, it is difficult to establish an adequate methodology for the modeling of the energy baseline. In this context, it is necessary to normalize the parameters that have characterized production; incorporating the factors and activities that represent a significant influence on energy consumption.

Whereas a line can now be established as a measured value up to a model based on simulations, some of the considerations made by ISO Standard 50006 are shown as an aid for the selection of an Energy Baseline showing a useful method.

Several types of Energy Baselines that companies can use according to ISO Standard 50006 are shown in Table 1.

Table 1. Type of Energy Baselines recommended by ISO Standard 50006.

Energy Baseline Type	Uses
Energy Value Measurement (kWh/day ; $kWh/month$; $kWh/year$)	- Measuring energy consumption savings. - Achieving legal requirements based on total savings. - Monitoring and control of stocks and energy costs. - Understanding energy consumption trends. - Obtained when the energy consumption measurement is given by a meter, with or without an energy conversion factor.
Measured Value ratio ($kWh/production$; kWh/m^2)	- Monitoring of the energy efficiency of systems that have a single relevant variable. - Monitoring systems where there is minimal or no base load. - Standardization of benchmarks between multiple facilities or organizations (benchmarking). - Understanding energy efficiency trends. - Can be used to express the energy efficiency of an item of equipment or system.
Statistical Model Linear Regression Model Non-linear regression model Multivariable model	- Systems with several relevant variables - Systems with a base load of energy consumption. - When the comparison requires untagging. - Modeling of complex systems where the correlation between energy performance and relevant variables could be quantified. - Energy performance at the organizational level with several relevant variables. - It shows the link between energy consumption and relevant variables.
Engineering or Simulation Model	- Evaluation of energy performance variation due to operational changes when there are many variables. - Processes and systems involving dynamic feedback cycles. - Systems with interdependent relevant variables (such as temperature and pressure). - Energy performance estimation at a design stage.

As such, it is important to consider the steps involved in implementing an Energy Baseline. First, begin with the definition of physical limits and organizations where the Energy Baseline is to be established; then, complete the identification of primary or secondary energy sources; next, the detection of significant variables with a greater impact on energy consumption within the boundaries established must occur; then, the acquisition of necessary information in the selected base period. All of these steps must occur in order to finally quantify the Energy Baseline from the chosen method, keeping in mind the complexity of the facilities where it needs to be implemented.

In this research paper, the analysis shows the line regression model as well as some considerations to bear in mind concerning the energy production ratio and its influence on the statistical analysis.

Regression analysis is a statistical technique used for modeling and analysis of the ratio between two or more variables [33].

The proposed methodology is focused on the standardization of production data to establish a baseline in accordance with regulatory requirements. These are necessary elements for finding energy consumption references that make it possible to establish savings targets, evaluate the balance between consumption and efficient technology, as well as implement energy indicators to evaluate energy performance and reduce emissions in the establishment of a SGEn management system. This would complete the SFA or DEA production boundaries models that are useful in determining an organization's overall efficiency and its connection to both production and efficiency aspects, as well as market assessments and benchmarking [34].

In an optimum manufacturing process, any variability in energy consumption should be explained by the fundamental link to production, with this being the most significant variable. A linear regression analysis could be used to build an Energy Baseline as a model for predicting th energy consumption of a given production.

Figure 1 shows the Energy Baseline established using linear regression analysis.

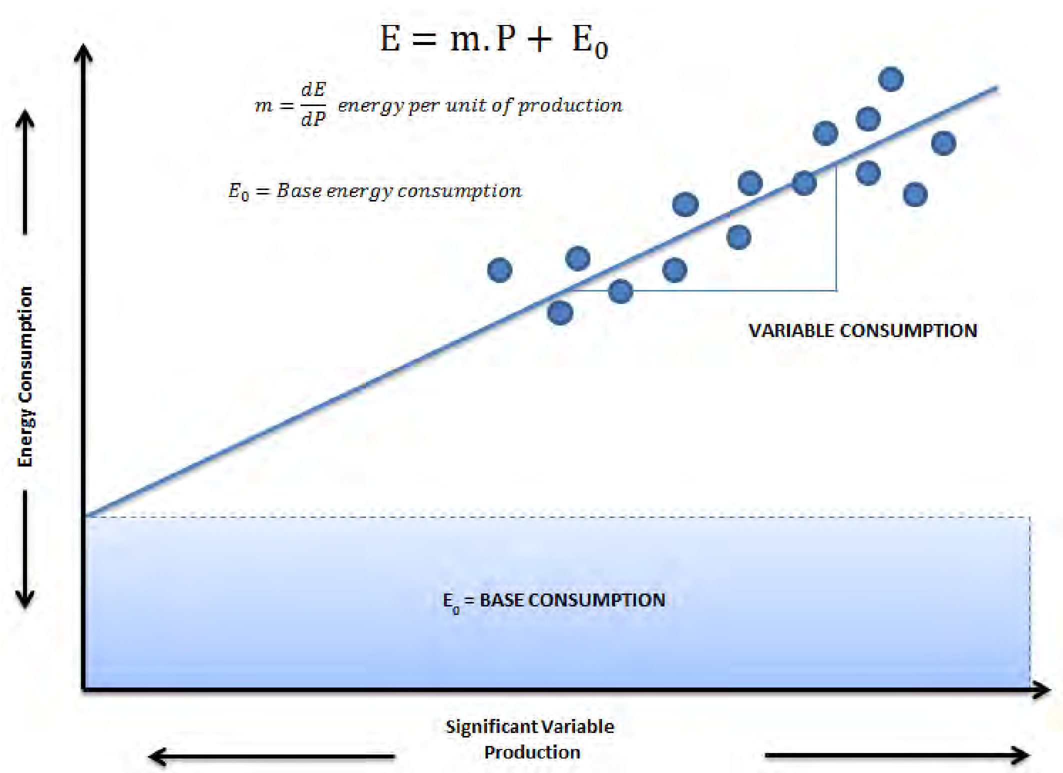

Figure 1. The Energy Baseline estimated as a linear regression model.

The interpretation of this figure is based on the fact that energy consumption is linearly related to the production level through Equation (1):

$$E = m{\cdot}P + E_0 \quad (1)$$

where there is constant energy consumption, E_0, which does not depend on the production carried out, and another variable part required to transform the raw material, $m{\cdot}P$. However, in a large industry with several energy sources and with complex uses of energy applied to several products at different times throughout the year, choosing and establishing an appropriate Energy Baseline type may take time and require efforts based on analysis, through the establishment of statistical or mathematical models [35–37].

This situation requires the use of tools that allow the standardization of energy data in order to deal with influencing factors, as recommended by the ISO Standard 50006. In this context, energy consumption often varies depending on the complexity of the facilities, due to variables such as the production levels (installed Capacity), raw materials, production technologies, maintenance techniques, management, and product types, among others, as shown in Figure 2.

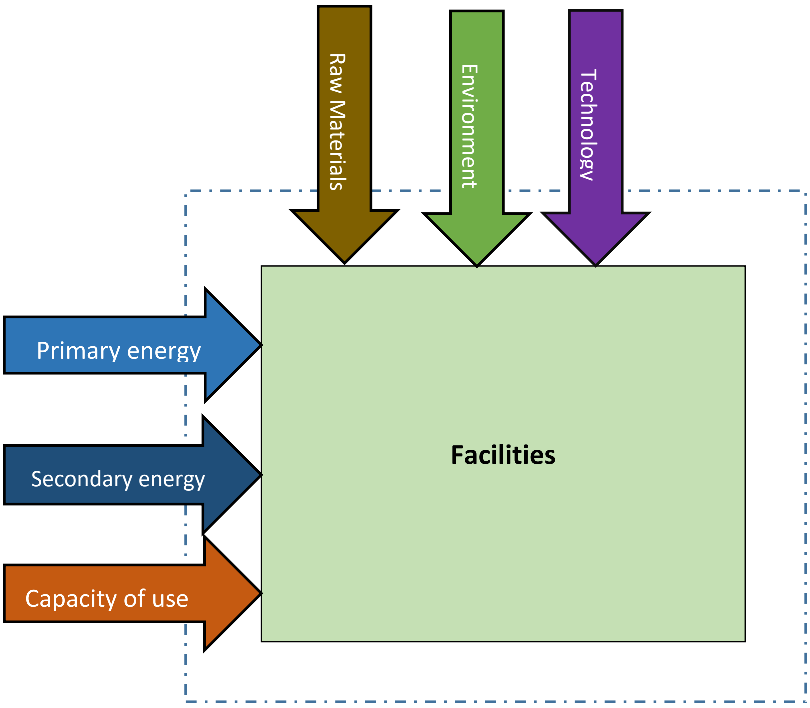

Figure 2. Significant variables that may affect the facilities.

Normalization is a term that is used broadly and can have substantially different meanings in different fields and applications. In this context, normalization is being used to describe the process of modeling energy consumption data with respect to relevant variables in order to compare energy performance under equivalent conditions. Typically, statistical methods such as linear regression are used to normalize or model energy consumption with respect to relevant variables [27].

For this reason, normalizing an Energy Baseline consists of identifying the significant variables that affect the energy consumption of an installation, and modeling it using some mathematical or statistical method that precisely determines a reference based on the energy performance to be evaluated, as a result of specific actions. This does not mean the influence of the operating condition of the installation.

It is sometimes possible to obtain an Energy Baseline with a low quadratic correlation coefficient (R^2). In such a procedure, after carrying out a data analysis, if it is concluded that there is a weak ratio between the variables, then this is due to the dynamics of the process itself and, therefore, it is important to normalize it through the addition of other relevant variables that affect energy consumption [38].

On the other hand, in some production models during a certain production period, while some units are started, not all of them are finished. In others, different products are made from the same raw material, either by means of different production lines or by variation of a manufacturing plan.

For such production models, it is often quite difficult to establish an adequate production term (P) for the Energy Baseline modeling. As a result, the factors and activities that have a significant influence on energy consumption should be standardized by incorporating them into the parameter characterizing production.

This is addressed through the use of the equivalent production method, which provides a presentation of the incomplete product (production stored in intermediate stages), depending on the finished product or the term of different products in a single global production.

In reality, the equivalent production method is specifically applied in two typical production situations, where energy consumption must be standardized in order to obtain an adequate energy baseline. The first is when the time interval in which energy is measured is not sufficient to transform all the raw material and production remains in process. The other is when, using one raw material, several products with different energy consumptions are made.

Thus, a case of productive models requiring the application of this method is described by performing mathematical modeling for the calculation and validating the proposed methodology in a case referred to the plastic industry.

The methodology for establishing the applied energy baseline for multiple production from a single raw material is presented. In this case, a single basic material gives rise to several products, which can be produced using the same technology, but with different production methods or through different production lines. At the end of an operating period, each finished product has different energy requirements associated with it.

Figure 3 shows the methodology used to establish the energy baseline, detailing the steps to be implemented, which include the statistical processing of the data.

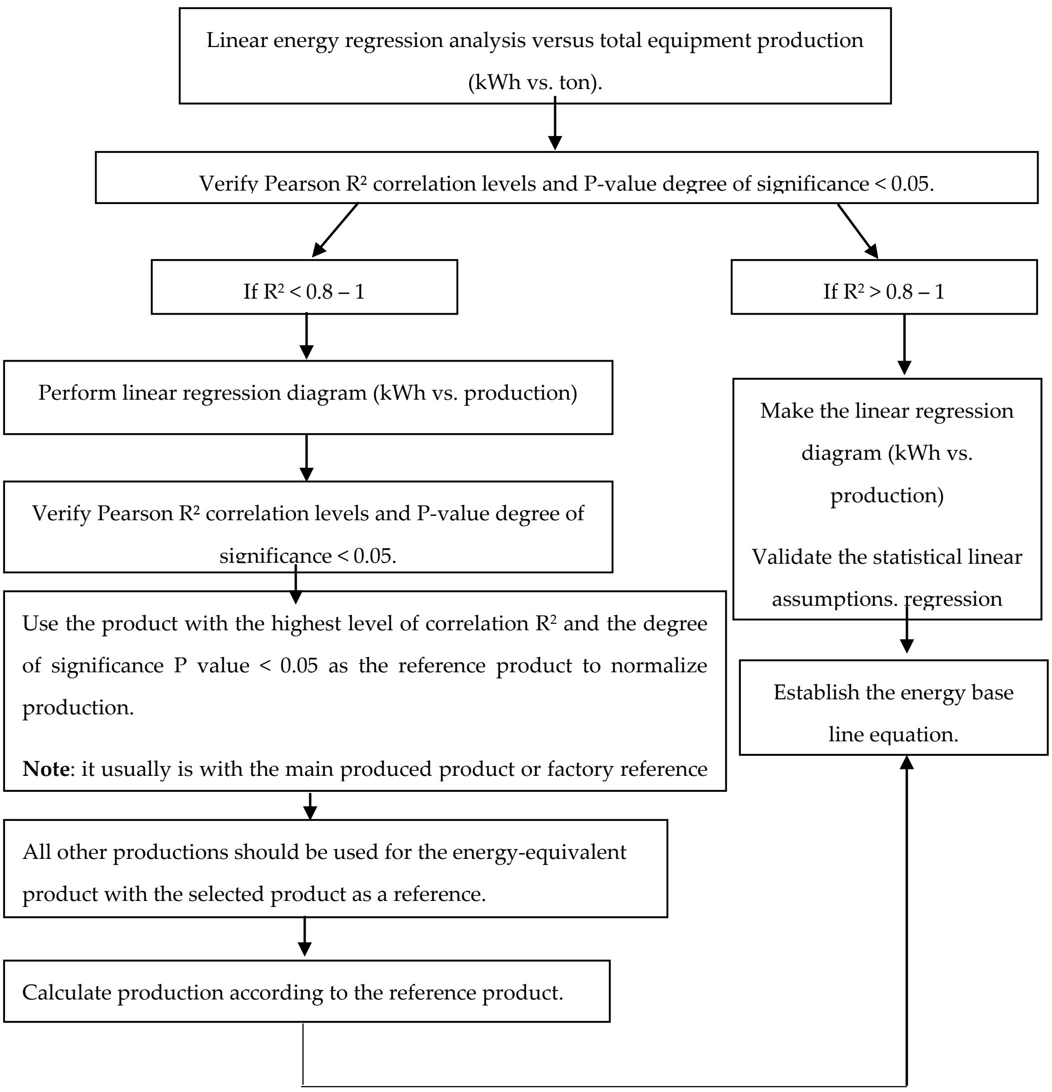

Figure 3. Methodology of production standardization, in order to establish an Energy Baseline.

In order to quantify the equivalent production in this process, it is necessary to select the product with the highest importance in the production model as the main or reference product. This can usually be the one that consumes the most energy at the end of the process. For this reason, the other products must be converted mathematically into an equivalent number of units of the one selected as the principal.

To carry out this calculation in a determined period, it is necessary to measure the quantity or units of the product established and those not established as references. At the same time, calculate the energy expenditure or consumption in each stage of the process while considering the type of production for which this consumption has been made. The next production model shows this scenario (Figure 4).

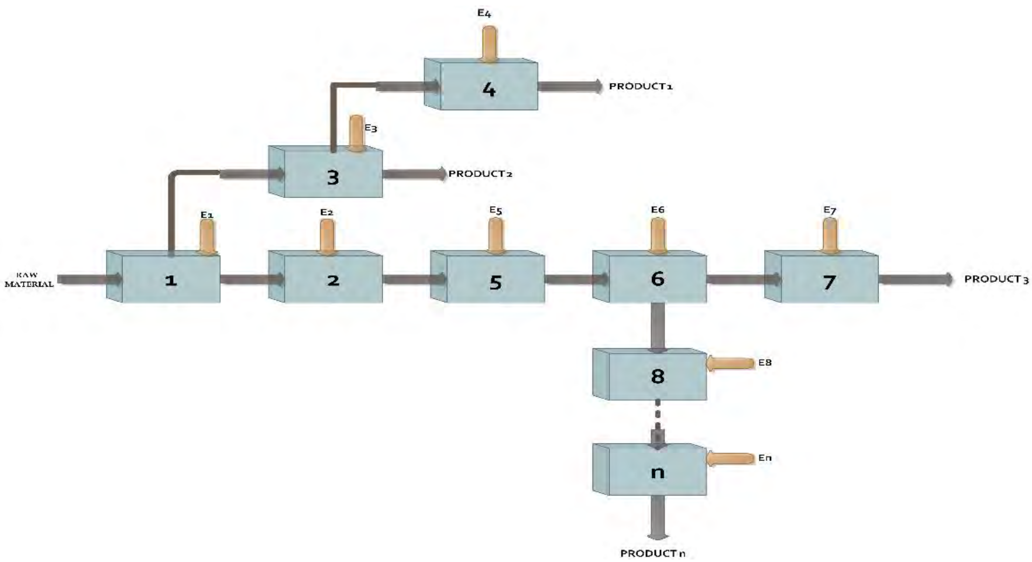

Figure 4. A Multi-Production Model made from a single Raw Material.

From this point of view, the following expression is mathematically posed for the calculation of the equivalent production in such processes, according to Figure 4.

Taking product 3 (P_3) as the $\boldsymbol{E_{equivalent}}$ reference (2):

$$P_{Equivalent} = P_3 + P1_{(Equivalent\ P_3)} + P2_{(Equivalent\ P_3)} + \ldots + Pn_{(Equivalent\ P_3)} \tag{2}$$

where it is indicated how the production data should be normalized according to the product or reference that has more energy expenditure, in this case P_3. This allows us to add the tons produced in terms of equivalent tons of product and removes the influence of the reference on energy consumption.

$P_1, P_2, \ldots\ P_n$ are calculated according to the reference product (P_3). These equations are determined as the quantity of the product from a type of production that consumes the same amount of energy as one tonne of the reference production (3):

$$P1_{(Equivalent\ P_3)} = \frac{IC_1}{IC_3} \times P_1; \quad P2_{(Equivalent\ P_3)} = \frac{IC_2}{IC_3} \times P_2; \quad Pn_{(Equivalent\ P_3)} = \frac{IC_n}{IC_3} \times P_n \tag{3}$$

where IC_1 , IC_2,IC_3, IC_4 . . . ..IC_n, are the consumption indicators of the end product n, which correspond to the expenditure on energy that each product has had as a function of the quantity produced from it.

E_1, E_2 , E_3, E_4, E_5........ E_n refer to the energy consumed by each reference or product in the process analyzed (4)

$$IC_1 = \frac{E_1 + E_2 + E_4}{P_1};\ IC_2 = \frac{E_1 + E_3}{P_2};\ IC_3 = \frac{E_1 + E_2 + E_5 + E_6 + E_7}{P_3};\ IC_n = \frac{E_1 + E_2 + E_5 + E_6 + E_8 + \ldots + E_n}{P_n}. \tag{4}$$

Finally, the energy baseline is made up of the energy consumption versus the equivalent tons of product produced in the line analyzed.

3. Analysis and Results

The model proposed below is applied to a case of an energy baseline for multiple production steps, using a single raw material fed to a plastic injection machine. A plastic injection machine produces multiple products in a period of time and varies according to the requirements of the program. Figure 5 shows the process diagram.

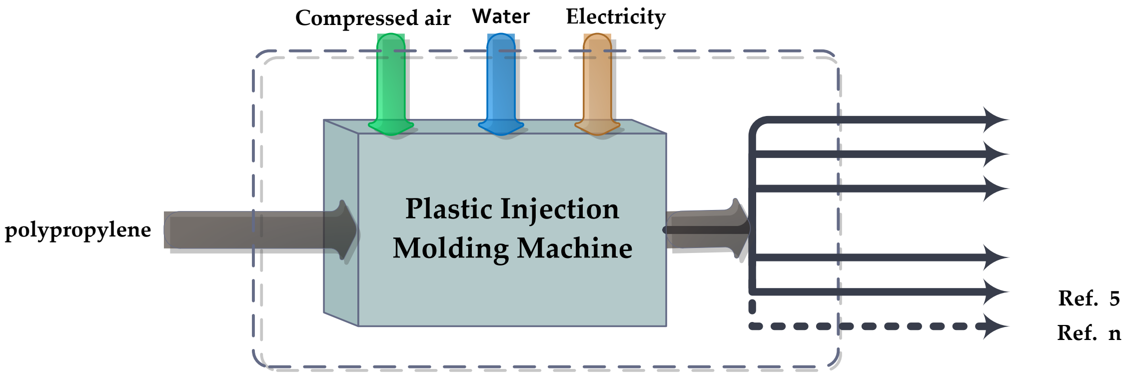

Figure 5. Plastic Injection Molding Machine process diagram.

This machine produces 380 different references, so establishing an energy baseline can be quite difficult. It is usually done by considering the total production of the equipment, as the sum of the kilograms of the different references produced, for the period of recording analysis and data collection. However, this situation is inappropriate, since, as shown below, making different references implies having various associated energy requirements ($kWh/kg \cdot item$).

Figure 6 shows the energy baselines of the most significant references, in other words, those that are most often manufactured on the machine. The efficiency of this equipment varies from 0.13 kWh/kg to 2.3 kWh/kg, depending on the type of product manufactured.

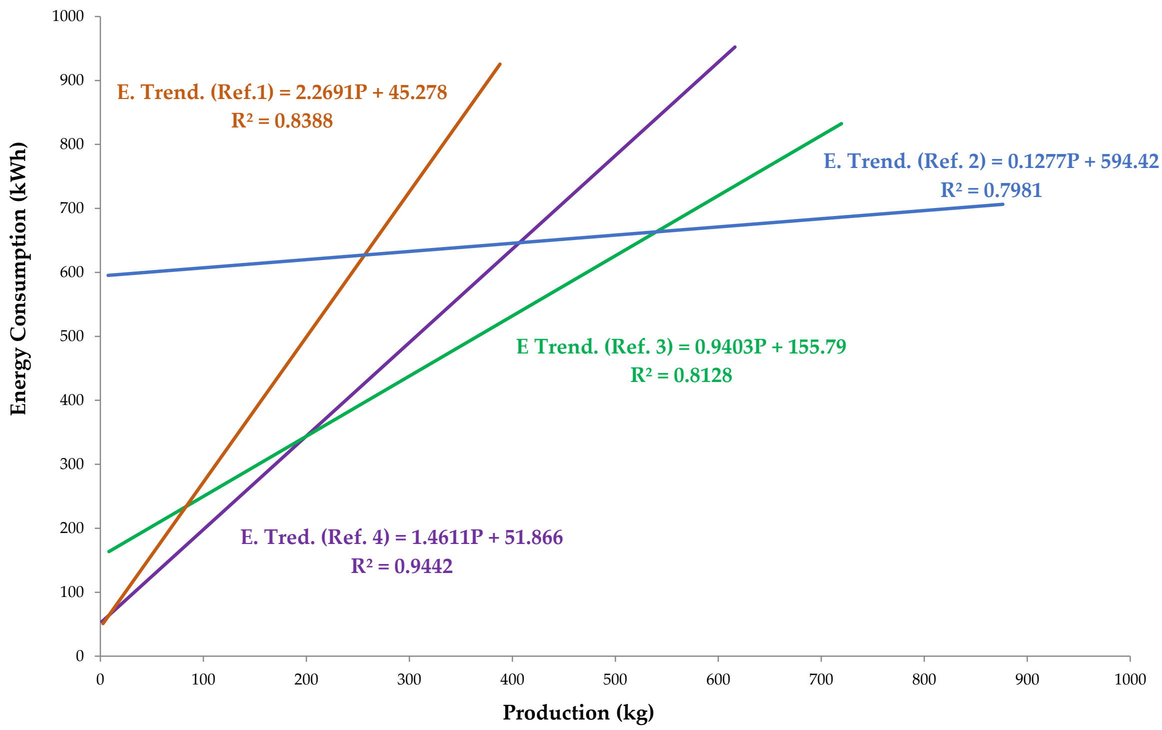

Figure 6. Energy requirements for the production of different models on a plastic Injection Molding Machine.

Figure 7 shows the daily energy consumption compared to the production carried out in the same period. A high dispersion of the data is observed, as well as little correlation between the variables. This shows how much important it is to normalize the Energy Baseline.

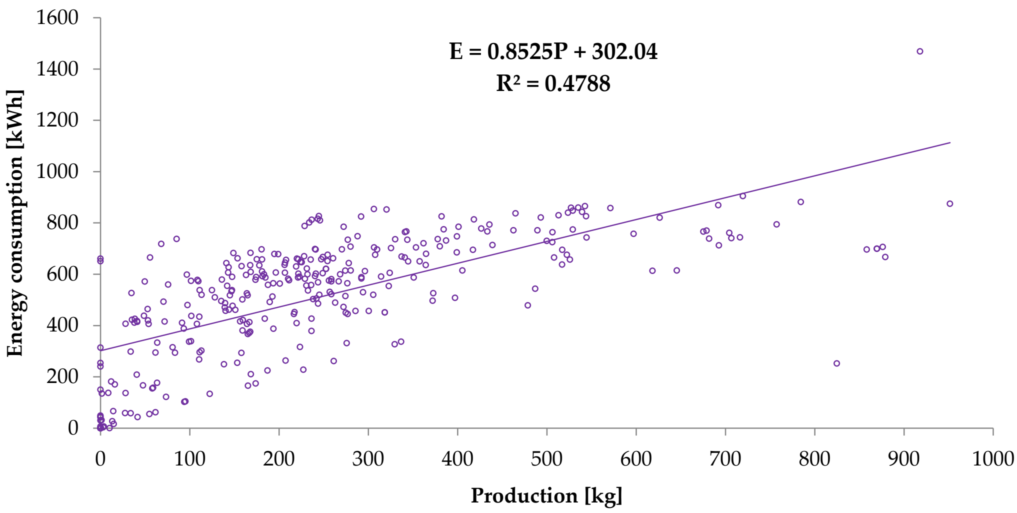

Figure 7. Energy Baseline for a plastic Injection Molding Machine.

Normalizing production for this kind of process is suitable for an Energy Baseline. In this case the product 4 is taken as reference, because it is the product that is most commonly used in the machine, and the one that has the best correlation with production in the linear regression analysis carried out for each product. To prepare the equation of production normalization of the analyzed machine, all the references produced to the selected product are taken as reference for this case, which is reference 4.

This equation allows us to find a general energy baseline for the whole machine and to forecast savings and goals per machine rather than per each reference produced.

The energy consumption records of the equipment, and the daily reference production, are used to estimate the Energy Baseline equation as Equation (5):

$$E_{Ref_4} = 1.4611P + 51.866. \quad (5)$$

This is selected as a reference because it corresponds to the one that is mainly produced in the machine. The other references are mathematically converted into equivalents of Ref_4. (6) [38,39]:

$$P_{Equiv.} = P_{Ref.4} + P_{Ref.1(Equiv.P_{Ref.4})} + P_{Ref.2(Equiv.P_{Ref.4})} + P_{n(Equiv.P_{Ref.4})} \quad (6)$$

where:

P_{Ref_4} = Production used as reference
$P_{Ref_1\ (Equivalent_{Ref4})}$ = Production of Product 1, equivalent to the reference product.
$P_{Ref_2\ (Equivalent_{Ref4})}$ = Production of Product 2, equivalent to the reference product.
$P_{Ref_n\ (Equivalent_{Ref4})}$ = Production of Product n, equivalent to the reference product.

The production calculation based on the reference product is obtained as Equation (7):

$$P_{n_{(Equivalent\ P_{Ref4})}} = P_n \times \left(IC_{actual_n} / IC_{n_{Ref4}}\right). \quad (7)$$

Being $IC_{n_{Ref4}}$, the consumption indicator of the reference product, for the production level where P_n , the executed production of a reference, is evaluated and calculated as Equation (8):

$$IC_{n_{Ref4}} = \frac{Equation\ of\ Reference\ Energy\ Base\ Line}{Reference\ product\ production} = \frac{mP_4 + E_0}{P_{n4}}. \quad (8)$$

Being IC_{actual_n}, the consumption indicator, calculated from the ratio between the measured energy consumption and the production carried out for the P_n (9):

$$IC_{actual_n} = \frac{E_{actual}}{P_n}. \quad (9)$$

$IC_{Company}$: the consumption indicator set up by the company to establish compliance goals.

Appendix A, shows the data obtained from Equations (6)–(9), which relate the variables production, energy consumption, normalized production (Pequiv), and consumption rates, allowing the monitoring of energy performance.

Finally, in Figure 8, the energy baseline is estimated again. It shows an increase in the correlation coefficient of 51%, compared to the initially estimated values. The new correlation coefficient indicates a strong correlation between the variables, therefore, the normalized energy baseline is suitable.

Non-production savings are estimated as the difference in the intercept (67.933 – 45.747) of the E_{base} and E_{meta} equations.

In addition, the statistical assumptions of the linear regression model were verified by the global test (GVLMA) and Rstudio Integrated Development Environment (IDE) [40]. All assumptions of the linear model are hereby validated as satisfied. Thus, the linear model can be used to measure electricity consumption in the analysis period according to the independent variable in this case (equivalent production).

The model of standardization of production reliably represents the behavior of the variation of the consumption with the variation of the equivalent production, because it eliminates the influence of the material or the reference produced in the consumption of energy.

Table 2 shows the non-standardized and standardized consumption equations of the injection molding machine. It complies with statistical requirements and can be used as a reference element to quantify energy expenditure, implement reliable efficiency indicators, budget monthly and annual energy expenditure, and establish energy goals that contribute to the efficient management of energy resources. This is due to the energy costs of the injection machines in the factory, which can be about 60% of the total consumption of the facility, according to studies carried out in Colombia [41].

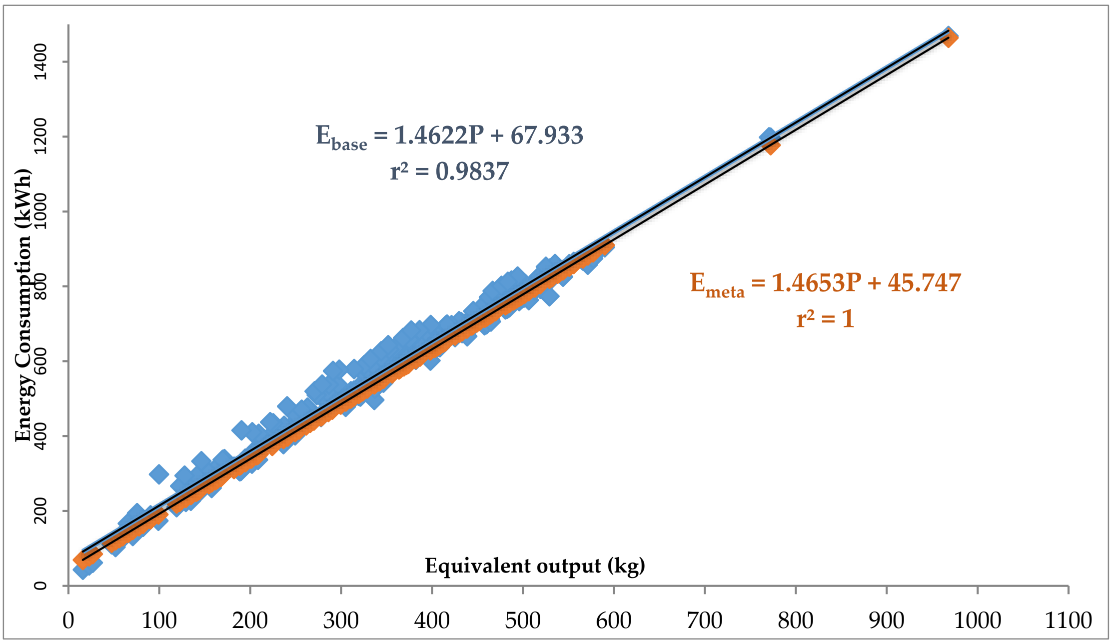

Figure 8. Standardized Energy Baseline for a Plastic Injection Molding machine using the equivalent production method.

Table 2. Estimated Energy Baselines for the I_18 Injection Molding Machine.

Injection Mold		Energy Baseline	Correlation Coefficient R^2	Target Line
	Unstandardized Energy Consumption Equation	E = 0.8525P + 302.04	0.478	-
H246	Ref_1	E = 2.2691P + 45.278	0.8388	2.2691P + 12.166
H110	Ref_2	E = 0.1277P + 594.42	0.7981	0.1277P + 581.89
H429	Ref_3	E = 0.9403P + 155.79	0.8128	0.9403P + 93.822
H332	Ref_4	E = 1.4611P + 51.866	0.9442	1.4611P + 22.51
	Standard energy consumption	$E = 1.4622P_{equiv.} + 67{,}9331$	0.9837	1.4622P + 45.747

The apply of the methodology presented above to establish baselines in the industry, combined with non-parametric frontier analysis, allows for a global analysis of the possibilities of improving energy efficiency in a sector with high energy consumption, such as the plastics industry. This is interesting for establishing compliance with energy targets established in the country. For each mold selected, it is possible to propose a target line, as well as a new baseline for the data processed using the production standardization method to give a proposal for energy savings per each injection molding machine.

Table 3 shows the equations of the Energy Baselines of each mold and the injection molding machine in order to propose their respective target line.

Table 3. Summary of Baselines and Target Lines of Selected Molds and Injection Molding Machines.

Injection Molding Machine	Mold		Energy Baseline	Correlation Coefficient R^2	Target Line
H-1		Unstandardized Energy Consumption Equation	0.769P + 1225	0.721	-
	H241		0.5511P + 1937.5	0.8156	0.5511P + 1803.7
	H198		0.7882P + 1022.6	0.8419	0.7882P + 703.15
	H187		1.2325P + 888.93	0.9121	1.2325P + 644.42
	H007		0.7115P + 1523.4	0.6409	0.7115P + 1309.7
	H118		0.6985P + 1492.3	0.8489	0.6985P + 1315.7
	H447		1.0082P + 770.44	0.9959	1.0082P + 683.68
	H446		0.6504P + 1733.1	0.9719	0.5604P + 1689.1
		Standardized Energy Consumption Equation	0.597P + 1830	0.864	0.597P + 1670
H-17		Unstandardized Energy Consumption Equation	0.445P + 23.66	0.348	-
	H377		0.5418P + 21.85	0.9024	0.5418P + 12.894
	H378		0.5871P + 12.708	0.9736	0.5871P + 8.6984
	H408		0.531P + 60.24	0.979	0.531P + 53.578
	H259		0.5838P + 36.849	0.9778	0.5838P + 27.669
	H292		0.1684P + 441.83	0.6115	0.1684P + 386.27
		Standardized Energy Consumption Equation	0.5494P + 12.22	0.9985	Negligible
I-11		Unstandardized Energy Consumption Equation	0.095P + 14.58	0.102	-
	H329		0.0265P + 27.167	0.8035	0.0265P + 22.348
	H388		0.025P + 34.22	0.5972	0.025P + 26.681
	H197		0.022P + 29.474	0.6714	0.022P + 26.235
	H206		0.023P + 37.76	0.598	0.023P + 33.56
	H477		0.045P + 13.82	0.792	0.045P + 10.90
		Standardized Energy Consumption Equation	0.0481P + 12.744	0.9386	0.0481P + 5.5258
I-18		Unstandardized Energy Consumption Equation	0.721P + 351.1	0.427	-
	H332		1.4611P + 51.866	0.9442	1.4611P + 22.51
	H429		0.9403P +155.79	0.8128	0.9403P + 93.822
	H246		2.2691P + 45.278	0.8388	2.2691P + 12.166
	H110		0.1277P + 594.42	0.7981	0.1277P + 581.89
		Standardized Energy Consumption Equation	1.4622P + 67.933	0.9837	1.4622P + 45.747

In the case study, energy savings were estimated in the entire line of 1106.900 $kWh/year$, showing an economic savings of 235,141,920 COP (Colombian pesos), 67,067.70€, and a decrease of $213,039.1\ kgco_2/year$.

Savings potentials of 1318 kWh⁄day and 613.5 kWh⁄day, for a total of 1932 kWh⁄day from the entire injection molding process, were identified from the analysis.

4. Conclusions

This research paper involves the establishment of energy baselines as a starting point for quantifying savings related to energy consumption, while evaluating improvements from the implementation of efficient technology as a basis for the energy management. The main objective is to reduce consumption, reduce emissions, and lead to cleaner production in Colombian industry. In this context, the implementation of energy management systems in the industry aligned with standards such as ISO Standard 50001 becomes relevant. However, finding the relationship of energy versus production is difficult because it means quantifying the units produced in the industry and the measurement of energy consumption related to each product. This is where the proposal presented in this research paper develops a new way of standardizing production schemes through mathematical models that outline the relationship between energy and production, using linearization models that respond to linear equations. In these models, it will be possible to carry out energy consumption monitoring and quantify the influence of the production variable in the plastic industry, which demands high consumption in the injection processes.

Therefore, the complexity of production models in industrial companies requires the standardization of certain variables that influence energy consumption. Thus, the purpose of establishing an Energy Baseline as a reference for correctly evaluating energy performance in accordance with the requirements of the ISO Standard 50001 is carried out.

The production standardization method is a useful tool because it allows us to standardize the production term in schemes where there are inventories of semi-processed material in intermediate stages, or when different products are obtained from the same raw material. Thus, we can achieve adequate references for the evaluation of energy performance over time.

The case study focuses on the plastic manufacturing process, which due to its production scheme, requires a methodology to standardize the term production in relation to energy consumption as a starting point for establishing an energy baseline. This applied methodology is exportable to the global production of the plastic industry with the aim of reducing carbon emissions and energy consumption.

In this context, the methodology is important for the correct evaluation of the energetic performance through indicators and, for the optimization of the planning of the production framed towards the increase of the energetic efficiency of the processes.

In this case, the methodology used for the Energy Baseline analysis made it possible to conduct an analysis of the efficiency of each of the injection molding machines, and made it possible to select the same machines according to the demand of the company and the most efficient injection molding machines for production of a given reference. This is particularly important for a sector such as plastics, which in Colombia represents high energy consumption area and an increasing growth industry for the country's economy.

For this purpose, Energy Baselines were established for each reference made in the injection molding machine. Similarly, an Energy Baseline was proposed to measure the savings potentials of all machines, using the model of standardization of production data according to ISO Standard 50006 recommendations and applying it to the four machines that presented inconsistency of rotation and permanence of the molds.

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Appendix A

Table A1. Consumption and Production Indicators.

Production (kg)	Energy (kWh)	IC_{actual_n} (kW/kg)	Standard Production P(Equiv.)	$IC_{n_{Ref4}}$ (kWh/kg)	$IC_{Company}$ (kWh/kg)
41.53	43.08	1.04	15.90	3.10	2.0
54.74	54.74	1.00	22.72	2.70	2.0
61.62	61.62	1.00	26.76	2.56	2.0
59.02	111.00	1.88	47.44	2.61	2.0
95.14	103.70	1.09	51.69	2.18	2.0
73.45	121.19	1.65	55.92	2.39	2.0
76.58	127.25	1.66	59.51	2.35	2.0
58.00	154.27	2.66	65.50	2.63	2.0
58.91	156.70	2.66	66.92	2.62	2.0
122.35	133.36	1.09	70.75	2.02	2.0
63.37	176.54	2.79	77.44	2.53	2.0
111.70	158.02	1.41	82.07	2.07	2.0
111.70	158.02	1.41	82.07	2.07	2.0
83.83	187.77	2.24	90.28	2.27	2.0
83.83	187.77	2.24	90.28	2.27	2.0
173.88	173.88	1.00	98.83	1.85	2.0
137.39	224.80	1.64	122.27	1.96	2.0
137.39	224.80	1.64	122.27	1.96	2.0
187.06	224.47	1.20	129.12	1.83	2.0
227.23	227.23	1.00	134.51	1.76	2.0
138.25	248.85	1.80	135.52	1.95	2.0
116.23	268.25	2.31	140.64	2.05	2.0
116.23	268.25	2.31	140.64	2.05	2.0
186.04	248.30	1.33	142.71	1.83	2.0
186.04	248.30	1.33	142.71	1.83	2.0
152.81	259.75	1.70	144.26	1.91	2.0
152.81	259.75	1.70	144.26	1.91	2.0
133.44	285.82	2.14	154.52	1.97	2.0
133.44	285.82	2.14	154.52	1.97	2.0
261.32	261.32	1.00	157.46	1.72	2.0
146.12	294.02	2.01	161.90	1.93	2.0
146.12	294.02	2.01	161.90	1.93	2.0
146.12	294.02	2.01	161.90	1.93	2.0
157.83	293.20	1.86	163.82	1.89	2.0
149.89	302.62	2.02	167.46	1.92	2.0
140.16	307.14	2.19	167.73	1.95	2.0
140.16	307.14	2.19	167.73	1.95	2.0
182.19	317.72	1.74	181.99	1.84	2.0
182.19	317.72	1.74	181.99	1.84	2.0
309.19	306.58	0.99	188.22	1.68	2.0
309.19	306.58	0.99	188.22	1.68	2.0
309.19	306.58	0.99	188.22	1.68	2.0
322.76	307.13	0.95	189.38	1.67	2.0
322.76	307.13	0.95	189.38	1.67	2.0
322.76	307.13	0.95	189.38	1.67	2.0
182.36	339.58	1.86	194.54	1.83	2.0
182.36	339.58	1.86	194.54	1.83	2.0

Table A1. *Cont.*

Production (kg)	Energy (kWh)	IC_{actual_n} (kW/kg)	Standard Production P(Equiv.)	$IC_{n_{Ref4}}$ (kWh/kg)	$IC_{Company}$ (kWh/kg)
275.75	330.95	1.20	200.67	1.71	2.0
329.57	326.51	0.99	201.74	1.67	2.0
164.98	366.84	2.22	206.62	1.87	2.0
171.86	367.10	2.14	208.24	1.86	2.0
171.86	367.10	2.14	208.24	1.86	2.0
336.64	336.64	1.00	208.43	1.66	2.0
166.70	370.83	2.22	209.24	1.87	2.0
193.69	387.38	2.00	224.06	1.81	2.0
340.73	402.23	1.18	249.32	1.66	2.0
236.42	426.43	1.80	253.76	1.75	2.0
216.58	444.60	2.05	261.44	1.78	2.0
217.28	451.91	2.08	265.86	1.77	2.0
276.78	444.95	1.61	269.91	1.71	2.0
285.66	456.20	1.60	277.72	1.70	2.0
318.44	451.16	1.42	277.81	1.68	2.0
300.56	456.50	1.52	279.43	1.69	2.0
272.26	472.15	1.73	285.87	1.71	2.0
243.74	485.44	1.99	290.01	1.74	2.0
401.57	493.00	1.23	310.01	1.63	2.0
323.67	503.44	1.56	310.51	1.67	2.0
245.21	519.51	2.12	310.60	1.74	2.0
274.29	514.28	1.87	311.65	1.71	2.0
258.58	521.90	2.02	314.08	1.72	2.0
397.21	507.82	1.28	319.05	1.63	2.0
256.83	530.62	2.07	319.06	1.73	2.0
452.91	505.78	1.12	321.01	1.61	2.0
294.08	529.72	1.80	323.50	1.69	2.0
372.83	525.60	1.41	328.46	1.64	2.0
3190.22	496.79	0.16	336.27	1.48	2.0
516.77	526.34	1.02	337.08	1.59	2.0
322.94	553.67	1.71	341.41	1.67	2.0
276.42	564.63	2.04	342.46	1.71	2.0
487.00	542.94	1.11	346.35	1.60	2.0
292.20	583.43	2.00	356.05	1.69	2.0
314.34	590.91	1.88	363.39	1.68	2.0
350.83	587.10	1.67	364.90	1.66	2.0
360.60	592.00	1.64	368.86	1.65	2.0
392.54	591.90	1.51	371.51	1.64	2.0
324.03	604.79	1.87	373.06	1.67	2.0
296.30	611.88	2.07	373.98	1.69	2.0
434.19	603.82	1.39	382.03	1.62	2.0
1020.65	601.90	0.59	398.10	1.53	2.0
424.55	637.48	1.50	402.63	1.62	2.0
357.51	649.86	1.82	404.60	1.65	2.0
471.51	638.48	1.35	406.39	1.61	2.0
517.06	637.68	1.23	408.40	1.59	2.0
340.82	664.77	1.95	412.06	1.66	2.0
337.21	668.91	1.98	414.21	1.66	2.0
508.06	664.79	1.31	425.28	1.60	2.0
399.10	684.78	1.72	430.39	1.63	2.0
522.44	675.41	1.29	432.85	1.59	2.0

Table A1. *Cont.*

Production (kg)	Energy (kWh)	IC_{actual_n} (kW/kg)	Standard Production P(Equiv.)	$IC_{n_{Ref4}}$ (kWh/kg)	$IC_{Company}$ (kWh/kg)
353.41	703.97	1.99	437.83	1.65	2.0
417.22	694.78	1.67	438.23	1.63	2.0
380.14	708.45	1.86	443.46	1.64	2.0
361.79	720.54	1.99	449.09	1.65	2.0
462.83	707.09	1.53	449.47	1.61	2.0
439.16	713.65	1.63	451.90	1.62	2.0
387.12	731.11	1.89	458.35	1.64	2.0
377.72	736.73	1.95	460.92	1.64	2.0
399.23	747.33	1.87	469.72	1.63	2.0
433.26	766.56	1.77	484.92	1.62	2.0
243.33	815.72	3.35	487.21	1.74	2.0
426.45	777.84	1.82	491.46	1.62	2.0
401.02	784.61	1.96	493.33	1.63	2.0
435.73	793.20	1.82	501.98	1.62	2.0
664.02	788.90	1.19	512.54	1.56	2.0
418.31	813.11	1.94	512.97	1.62	2.0
757.42	793.88	1.05	519.02	1.55	2.0
320.36	852.14	2.66	525.04	1.67	2.0
513.05	829.68	1.62	531.10	1.59	2.0
464.92	836.86	1.80	532.13	1.61	2.0
523.59	839.35	1.60	537.99	1.59	2.0
527.00	859.04	1.63	550.84	1.59	2.0
542.66	865.12	1.59	555.75	1.59	2.0
784.45	881.14	1.12	576.96	1.55	2.0
951.44	874.56	0.92	577.04	1.53	2.0
553.87	1198.00	2.16	770.55	1.58	2.0
582.36	1197.25	2.06	772.34	1.58	2.0
918.00	1468.80	1.60	967.84	1.54	2.0

References

1. EU EPBD 2018/844/EU. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018L0844&from=IT (accessed on 5 October 2019).
2. EU EPBD 2010/31/EU. Available online: https://eur-lex.europa.eu/legal-content/ES/TXT/?uri=celex%3A32010L0031 (accessed on 5 October 2019).
3. EU EPBD 2012/27/EU. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1399375464230&uri=CELEX:32012L0027 (accessed on 5 October 2019).
4. International Energy Agency (IEA). Tracking Industry. Available online: https://www.iea.org/reports/tracking-industry-2019 (accessed on 5 October 2019).
5. International Energy Agency (IEA). *Energy Efficiency 2018—Analysis and Outlooks to 2040*; International Energy Agency: Paris, France, 2017; pp. 1–143.
6. ISO. ISO Survey 2017. Available online: https://www.iso.org/the-iso-survey.html (accessed on 8 October 2019).
7. Chakraborty, D. Environmental Management Accounting (EMA) and Environmental Reporting in a Resource Constrained World: Challenges for CMAs. *Manag. Account.* **2017**, *52*, 36–42.
8. Dzene, I.; Polikarpova, I.; Zogla, L.; Rosa, M. Application of ISO 50001 for Implementation of Sustainable Energy Action Plans. *Energy Procedia* **2015**, *72*, 111–118. [CrossRef]
9. Deloitte LATCO Análisis Económico y de Industrias Latinoamérica La hora de las reformas estructurales. Available online: https://www2.deloitte.com/content/dam/Deloitte/cr/Documents/finance/Deloitte-Analisis-Economico-y-de-Industrias-Latinoamerica.pdf (accessed on 10 October 2019).

10. Wang, H.; Chen, W. Modelling deep decarbonization of industrial energy consumption under 2-degree target: Comparing China, India and Western Europe. *Appl. Energy* **2019**, *238*, 1563–1572. [CrossRef]
11. Barrett, J.; Cooper, T.; Hammond, G.P.; Pidgeon, N. Industrial energy, materials and products: UK decarbonisation challenges and opportunities. *Appl. Therm. Eng.* **2018**, *136*, 643–656. [CrossRef]
12. Arce, G. *Plan de Acción Indicativo de Eficiencia Energética 2017–2022*; Ministerio de Minas y Energía, República de Colombia: Bogota, Colombia, 2017.
13. Ley de 1715. Available online: http://www.secretariasenado.gov.co/senado/basedoc/ley_1715_2014.htm (accessed on 10 October 2019).
14. International Organization for Standards (ISO). *ISO 50001: International Standard, Energy Management Systems—Requirements with Guidance for Use*; International Organization for Standards: Geneva, Switzerland, 2011.
15. Rey-Hernández, J.M.; Velasco-Gómez, E.; San José-Alonso, J.F.; Tejero-González, A.; González-González, S.L.; Rey-Martínez, F.J. Monitoring Data Study of the Performance of Renewable Energy Systems in a Near Zero Energy Building in Spain: A Case Study. *Energies* **2018**, *11*, 2979. [CrossRef]
16. Castrillon, R.; González, A.; Ciro, E. Mejoramiento de la eficiencia energética en la industria del cemento por proceso húmedo a través de la implementación del sistema de gestión integral de la energía. *Dyna* **2013**, *80*, 115–123.
17. International Energy Agency (IEA). *Indicadores de Eficiencia Energética: Bases Esenciales para el Establecimiento de Políticas*; International Energy Agency: Paris, France, 2015; p. 182.
18. Rey-Hernández, J.M.; Velasco-Gómez, E.; San José-Alonso, J.F.; Tejero-González, A.; Rey-Martínez, F.J. Energy analysis at a near zero energy building. A case-study in Spain. *Energies* **2018**, *11*, 857. [CrossRef]
19. McKane, A.; Therkelsen, P.; Scodel, A.; Rao, P.; Aghajanzadeh, A.; Hirzel, S.; Zhang, R.; Prem, R.; Fossa, A.; Lazarevska, A.M.; et al. Predicting the quantifiable impacts of ISO 50001 on climate change mitigation. *Energy Policy* **2017**, *107*, 278–288. [CrossRef]
20. Kassai, M. Experimental investigation of carbon dioxide cross-contamination in sorption energy recovery wheel in ventilation system. *Build. Serv. Eng. Res. Technol.* **2018**, *39*, 463–474. [CrossRef]
21. Kassai, M.; Simonson, C.J. Experimental Effectiveness Investigation of Liquid-to-air Membrane Energy Exchangers under Low Heat Capacity Rates Conditions. *Exp. Heat Transf.* **2016**, *29*, 445–455. [CrossRef]
22. Kanneganti, H.; Gopalakrishnan, B.; Crowe, E.; Al-Shebeeb, O.; Yelamanchi, T.; Nimbarte, A.; Currie, K.; Abolhassani, A. Specification of energy assessment methodologies to satisfy ISO 50001 energy management standard. *Sustain. Energy Technol. Assess.* **2017**, *23*, 121–135. [CrossRef]
23. Pelser, W.A.; Vosloo, J.C.; Mathews, M.J. Results and prospects of applying an ISO 50001 based reporting system on a cement plant. *J. Clean. Prod.* **2018**, *198*, 642–653. [CrossRef]
24. Bonacina, F.; Corsini, A.; De Propris, L.; Marchegiani, A.; Mori, F. Industrial Energy Management Systems in Italy: State of the art and perspective. *Energy Procedia* **2015**, *82*, 562–569. [CrossRef]
25. Jovanović, B.; Filipović, J.; Bakić, V. Energy management system implementation in Serbian manufacturing—Plan-Do-Check-Act cycle approach. *J. Clean. Prod.* **2017**, *162*, 1144–1156. [CrossRef]
26. Benedetti, M.; Cesarotti, V.; Introna, V. From energy targets setting to energy-aware operations control and back: An advanced methodology for energy efficient manufacturing. *J. Clean. Prod.* **2017**, *167*, 1518–1533. [CrossRef]
27. International Organization for Standards (ISO). *ISO 50006: Energy Management Systems—Measuring Energy Performance Using Energy Baselines (EnB) and Energy Performance Indicators (EnPI)—General Principles and Guidance*; International Organization for Standards: Geneva, Switzerland, 2016.
28. Department of Energy (DOE). Steps to Develop a Baseline: A Guide to Developing an Energy Use and Energy. Available online: https://www1.eere.energy.gov/manufacturing/resources/pdfs/leaderbaselinestepsguideline.pdf (accessed on 5 October 2019).
29. Castrillón, R.; Gonzalez, A. *Metodología Para la Planificación Energética a Partir de la Norma ISO 50001*; Universidad Autónoma de Occidente: Cali, Colombia, 2018; ISBN 978-958-8994-59-8.
30. Castrillón, R.; Quispe, E.C.; Gonzalez, A.; Urhan, M.; Fandiño, D. *Metodología Para la Implementación del Sistema de Gestión Integral de la Energía. Fundamentos y Casos Prácticos*; Universidad Autónoma de Occidente: Cali, Colombia, 2015; ISBN 9789588713540.
31. The Northwest Energy Efficiency Alliance (NEEEA). *Energy Baseline Methodologies for Industrial Facilities*, 1st ed.; The Northwest Energy Efficiency Alliance: Portland, OR, USA, 2011.

32. Gómez-Calvet, R.; Conesa, D.; Gómez-Calvet, A.R.; Tortosa-Ausina, E. Energy efficiency in the European Union: What can be learned from the joint application of directional distance functions and slacks-based measures? *Appl. Energy* **2014**, *132*, 137–154. [CrossRef]
33. Morvay, Z.K.; Gvozdenac, D.D. *Applied Industrial Energy and Environmental Management*; John Wiley & Son: Hoboken, NJ, USA, 2009; ISBN 9780470697429.
34. Bogetoft, P.; Otto, L. *Benchmarking with DEA, SFA, and R*; Springer: Berlin, Germany, 2011; ISBN 978-1-4419-7961-2.
35. Sakamoto, T.; Takase, K.; Matsuhashi, R.; Managi, S. Baseline of the projection under a structural change in energy demand. *Energy Policy* **2016**, *98*, 274–289. [CrossRef]
36. Marina Domingo, A.M.; Rey-Hernández, J.M.; San José Alonso, J.F.; Crespo, R.M.; Rey Martínez, F.J. Energy efficiency analysis carried out by installing district heating on a university campus. A case study in Spain. *Energies* **2018**, *11*, 2826. [CrossRef]
37. Jentsch, M.F.; Bahaj, A.S.; James, P.A.B. Climate change future proofing of buildings-Generation and assessment of building simulation weather files. *Energy Build.* **2008**, *40*, 2148–2168. [CrossRef]
38. Sagastume Gutiérrez, A.; Cabello Eras, J.J.; Sousa Santos, V.; Hernández Herrera, H.; Hens, L.; Vandecasteele, C. Electricity management in the production of lead-acid batteries: The industrial case of a production plant in Colombia. *J. Clean. Prod.* **2018**, *198*, 1443–1458. [CrossRef]
39. Prias, O.; Campos, J.; Rojas, D.; Palencia, A. Implementación de un Sistestema de Gestión de la Energía. Guía con Base en ISO50001. 2013. Available online: http://reciee.com/pdf/2013%20-%20Implementaci%C3%B3n%20SGIE,%20Gu%C3%ADa%20con%20Base%20ISO%2050001%20(1).pdf (accessed on 15 October 2019).
40. Allaire, J.J.; Team, R.C. RStudio IDE for R. Available online: https://rstudio.com/ (accessed on 19 December 2019).
41. Vargas Isaza, C.A. *Consumo de Energía en la Industria del Plástico: Revisión de Estudios Realizados*; Instituto Tecnológico Metropolitano: Medellín, Colombia, 2015; Volume 1.

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