Master Thesis

METHODOLOGY DEVELOPMENT FOR SETTING ENERGY CONSUMPTION TARGETS IN THE SUPPLY CHAIN OF A TEXTILE MANUFACTURING AND DISTRIBUTION COMPANY

Author: Lucia de la Torre Rueda [1]
Supervisor: Francisco Aguirre [2]

[1] Affiliation 1; 201800409@alu.comillas.edu
[2] Affiliation 2; francisco.aguirre@arup.com

Abstract: This project consists of the methodology development for the establishment of energy consumption targets, (for both electrical and thermal (in kWh/kg of production) energy), for the supply chain of a textile manufacturing and distribution company, referred to throughout the document as *Client*. *Client's* objective consists of learning what the optimum energy consumption of the different stages of the textile production process should be, in order to transmit these objectives to its suppliers (the factories in which these processes are carried out). This analysis has been developed for the fabric exhaust dyeing textile manufacturing process. The methodology developed for the establishment of energy consumption objectives for this specific process includes a bibliographical analysis, a description of the audits carried out to gather the pertinent information, and the procedure followed for establishing the process' energy consumption targets.

Keywords: Energy, Textile, Efficiency, Objective, Consumption, Dyeing, Exhaust, Audit, KPI.

1. Introduction

Nowadays, considering the current complex environmental situation our planet faces, energy efficiency is one of the main challenges that different countries, sectors, and industries are facing. In particular, the textile industry is responsible for approximately 10% of the global carbon emissions, according to the European Environment Agency. The sector is therefore in the spotlight of regulatory bodies, such as the European Union, and awaiting possible future regulations.

Leading companies in the textile industry are aware of their activity's impact and are committed to the emission reduction targets adopted at global scale. The great challenge lies in the short term being able to establish what measures to take for the future achievement of these objectives.

The decarbonization of a company or a production process can be approached from two different perspectives: by focusing on energy efficiency, or, on the other hand, by focusing on the energy sources that supply the processes.

On the one hand, through energy efficiency measures, the objective of decarbonization is achieved by reducing the energy required in the process and, therefore, the emissions released into the environment.

On the other hand, the energy sources approach involves changing the current energy sources to cleaner ones, such as renewable energies, or emissions offsetting through diverse mechanisms such as green certificates.

This project focuses primarily on reducing emissions through energy efficiency, and more specifically, consists of the establishment of an energy consumption target, both electrical and thermal (in kWh/kg of production) for the fabric exhaust dyeing process in the textile manufacturing chain. These factories supply *Client*, but do not belong to *Client*.

As the emissions associated with textile production belong to *Client*'s Scope 3 emissions (emissions related to the supply chain), *Client* is interested in knowing what the optimum energy consumption for each production process should be, in order to be able to transfer this objective to its suppliers.

Optimum consumption is understood as that in line with the best available techniques in the industry, but at the same time technically and economically feasible for the factories.

2. State of the Art

Currently, there is no reference guide establishing these energy consumption target values, nor an analysis describing a methodology for measuring them. Part of the available information was developed over 10 years ago, meaning that technologies and, therefore, their energy consumption may have evolved since then. However, it must be considered that, on one hand, many processes have not evolved significantly, and on the other hand, proper maintenance of equipment, as well as the retrofit of energy efficient elements, can help maintain their efficiency. Therefore, for this initial analysis, the information collected is deemed acceptable despite its age.

Many of the consulted documents are based on the textile industry of a specific country and may not take into account the energy context of different countries. There is greater availability of information and studies in countries where the textile industry represents a significant sector of their national industry, such as Turkey and Bangladesh. In this regard, this is not considered an impediment, as these countries are major textile production hubs.

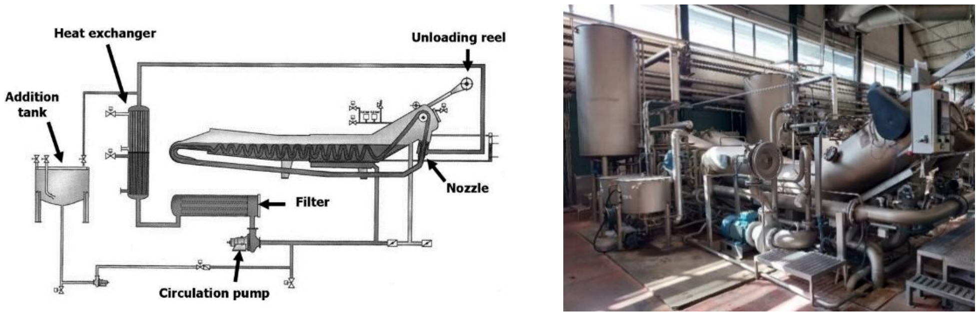
Finally, another factor that adds complexity to the analysis of the consulted literature and the conclusions that can be drawn from it is that each source obtains its data through different procedures. For example, in some cases, auxiliary consumption for heating or cooling and lighting is distinguished from production process consumption, while in other sources, the data do not include this distinction. Considering that, as will be verified later, these types of auxiliary processes can represent a negligible percentage of the total consumption of the facilities, this is not expected to pose a significant problem.

Regarding the fabric exhaust dyeing process, it is a process that is performed on fabrics, after their production process, and before the cutting and sewing final processes that lead to the obtention of the final garment. The process consists of dyeing fabrics in batches, rather than in continuous machines.

The process requires electricity, steam, and compressed air. This dyeing process can be performed using three main types of technologies [1]:

- Jet Technology

Jet technology is the most recent and efficient method within fabric exhaust dyeing processes. In this dyeing process, both the fabric and the dyeing water are continuously moved within the machinery. The dyeing water is propelled against the fabrics using a jet. The fabric is introduced into the machinery in a tubular form.



(a) **(b)**

Figure 1. Jet dyeing machine: (a) schematic diagram; (b) picture of a jet dyeing machine.

- Beck/Winch Technology

Beck/Winch technology is the oldest among the batch dyeing technologies. In this method, only the fabric is in motion, continuously entering and exiting the dye bath. The fabric is also introduced into the machinery in a tubular form. The speed of the fabric within these machines is significantly lower compared to that of Jet technology. Beck/Winch technology is commonly used for woolen fabrics, as they are usually more delicate than others.

(a) **(b)**

Figure 2. Beck/winch dyeing machine: (a) schematic diagram; (b) picture of a beck/winch dyeing machine.

- Jigger Technology

In Jigger technology, the fabric is introduced flat rather than in a tubular form. It is similar to Winch technology in the fact that the water mixture remains stationary while the fabric is in motion. Excess water is subsequently removed by passing the fabric through a series of squeezing rollers.

(a) **(b)**

Figure 3. Jigger dyeing machines: (a) schematic diagram; (b) picture of a jigger dyeing machine.

3. Objectives

As stated, the project's objective consists of the establishment of a series of KPIs on electrical and thermal specific energy consumption (in units of kWh per kg of production) for the Fabric Exhaust Dyeing process.

Firstly, several publications and academic studies on Fabric Exhaust Dyeing energy consumption are studied.

Afterwards, 19 facilities in which the Fabric Exhaust Dyeing process is carried out are visited. One of these factories is specifically evaluated, to show the kind of information gathered during the energy audits. This factory is located in Portugal, and alongside the Fabric Exhaust Dyeing process, the Fabric pretreatment and Fabric finishing processes are also carried out on its premises.

Finally, the establishment of energy consumption targets for this specific process (Fabric Exhaust Dyeing) is carried out, based on the variable identified as the most influential, whether the fabric is predominantly natural or synthetic.

4. Methodology

4.1. Bibliography study:

The first stage of the project involves studying the existing literature regarding the energy consumption of Fabric Exhaust Dyeing processes. Due to the disparity in process types, there is significant variability in energy consumption within factories. Additionally, factors such as the factory's location or the type and maintenance of its machinery can play an important role in its energy consumption.

To address this difficulty, this initial phase of bibliographic study and analysis of available benchmarks has been divided into three specific activities:

- <u>Bibliographic Research:</u> the objective of this study is to define benchmarks for specific consumption, both electrical and thermal (in kWh/kg of production) of the various textile production processes. Given the highly specific nature of the subject, the most reliable sources of information are considered to be those specialized in the sector, mainly academic studies and specialized scientific journals, such as the *Journal of Cleaner Production* or *Energy*. This bibliographic review allowed for the determination of energy consumption ranges (variation margins) for the Fabric Exhaust Dyeing production processes.
- <u>Determination of Specific Energy Consumption Ranges:</u> to establish the lower and upper limits of the energy consumption ranges for the fabric exhaust dyeing process, for the lower value of the range, the lower quartile (Q1, 25%) of the available data set is calculated. For the upper value of the process range, the upper quartile (Q3, 75%) of the available data set is calculated.

  Although the statistical technique of percentiles is designed for larger data sets, given the small available sample, this procedure is chosen to discard values that are below or above the general trend, with the chosen range being the corresponding interquartile range of the sample. Values considered outliers are those that fall outside the range defined beyond the first quartile minus 1.5 times the interquartile range, and the third quartile plus 1.5 times the interquartile range.

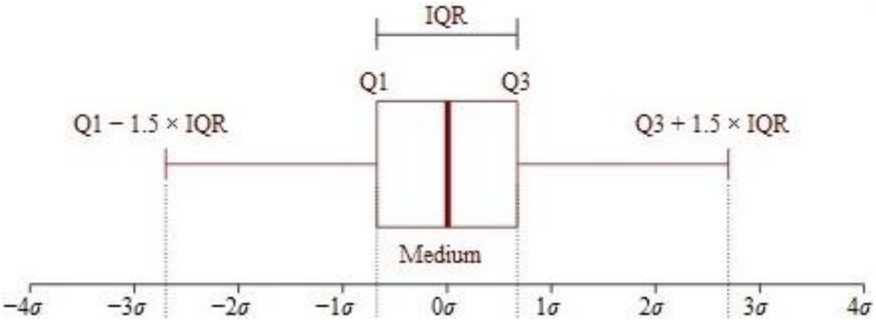


Figure 4. Interquartile range.

Following these 2 steps, from the information gathered from a series of sources [2,3,4,5,6], the following energy consumption ranges expected for the fabric exhaust dyeing process are calculated in Table 1:

Table 1. Fabric exhaust dyeing energy consumption expected ranges from bibliography.

Low range electricity (kWh/kg)	High range electricity (kWh/kg)	Low range thermal energy (kWh/kg)	High range thermal energy (kWh/kg)
0.41	2.55	1.3	7.4

4.2. Development of energy audits:

In addition to the bibliographic research carried out as the first phase of the project, 19 visits to fabric exhaust dyeing facilities were performed, to gather on-site data of the energy consumption of the processes and the variables involved. These visits provided detailed information on various parameters of the installations, including:

- Installation Details: characteristics such as size, number of workers and production schedules.
- Fibers Used: types of fibers processed in the dyeing facilities.
- Production Processes: description of the dyeing processes carried out, including their steps and variations.
- Energy Consumption: detailed data on both electrical and thermal energy usage during the dyeing processes.
- Auxiliary Equipment: information on auxiliary equipment used in the facilities, such as boilers, compressors, etc.
- Heating, Cooling, Ventilation, and Lighting Systems: data on the systems used for climate control and illumination.
- Energy Efficiency Rating: evaluation of the overall energy efficiency of each facility.

These visits allowed for a practical validation of the data obtained from the literature and helped refine the benchmarks for energy consumption in Fabric Exhaust Dyeing processes. The on-site data provided a comprehensive understanding of real-world practices and their implications on energy efficiency, contributing to a more accurate and context-sensitive analysis.

The following section provides a detailed analysis of one of the factories visited. It is important to note that, for confidentiality reasons, data such as the name or exact location of the facility have been omitted from this analysis. The factory is located in Portugal and primarily conducts batch dyeing of textiles.

4.2.1. Analysis of a specific Fabric Exhaust Dyeing facility in Portugal:

4.2.1.1. Facility details:

- Total floor area: 9000 sq. m.
- Total number of workers: 90.
- Working hours: 24 hours per day, 5 days per week.

4.2.1.2. Types of fibers processed:

As expected, considering the facility is a Fabric Exhaust Dyeing facility, the type of products processed within its premises are woven and knitted fabrics. The fabric arrives at these facilities in large rolls, with several meters in length and 2 meters in width. The composition of the processed fabrics within the analyzed facility is shown in the following table 2:

Table 2. Types of fibers processed in the Fabric Exhaust Dyeing facility analyzed.

Type of fiber	Percentage
Cotton	60%
Polyester	28%
Viscose	1%
Nylon	4%
Others	7%

4.2.1.3. Production processes:

As already explained, the visited factory's main process is Fabric Exhaust Dyeing. This process takes place after the fabric production process and before the cutting and garment manufacturing stages. These two preceding and subsequent stages to dyeing are, in this specific case, conducted in facilities independent to this one. More vertically integrated factories may carry out several independent processes within its premises.

In the specific facility visited, the following processes are specifically carried out, to complement the Fabric Exhaust Dyeing process:

- Fabric Pretreatment: these are processes that must be performed before dyeing the fabric. Pretreatment processes may be chemical, involving resin impregnation, or physical, including sewing or cutting activities. In this factory, a mechanical pretreatment (cutting and sewing of fabrics) and a chemical thermofixation in a stenter, conducted before dyeing, are specifically performed.
- Fabric exhaust dyeing: this is the stage where the fabric dyeing occurs. It also includes the subsequent rinsing of the fabric with water. As mentioned in this article's introduction, there are different exhaust dyeing technologies, such as Jet, Jigger, and Beck/Winch technologies.
- Cold Fabric Finishing: these are physical processes carried out on the dyed fabric to enhance its properties. In this facility, fabric reopening with a cutting machine is performed.
- Hot Fabric Finishing: similar to the previous processes, these are performed on the dyed fabric to enhance its properties. For hot finishes, these processes use heat to thermofixate the fabrics or impart flame-retardant, water-repellent, etc., properties. The finishing processes carried out in the factory are detailed below.

The following figure shows a schematic of the production process carried out in this specific facility, along with the energy sources required in each stem. This diagram was provided by the facility during the visit:

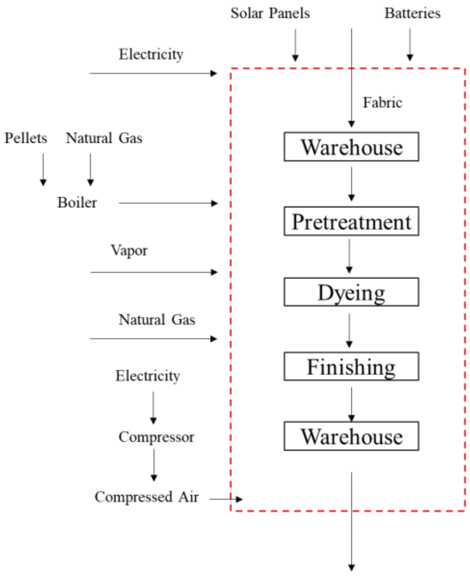


Figure 5. Production processes and system energy sources input for the factory analyzed.

It was also specified that the total facility's production throughout the year 2023 was 2,572,232 kilograms. The following sections provide a detailed description of the production processes carried out at the facility, along with the associated machinery and its characteristics:

4.2.1.3.1. Fabric pretreatment:

At this particular facility, two types of pretreatment processes are conducted on fabrics: a mechanical pretreatment and a thermofixation process.

The mechanical pretreatment process involves three machines:

- Two Unwinding Machines: these machines, from 2019, are used to unwind the fabric rolls that come into the facility so that they can be more easily transported and fed into the dyeing machines.
- One Sewing Machine: also from 2019, this machine is used to sew the fabric rolls, converting them from flat strips into tubular forms.

(a) **(b)**

Image 1. Fabric pretreatment machinery: (a) Sewing machine; (b) Unwinding machine.

The only energy source for the aforementioned machinery is electricity. These processes do not require any heat input, and thus, do not have any thermal consumption.

The next process to be performed in the facility after this first mechanical pretreatment is thermofixation. In the thermal fixation process, the fabric is subjected to high temperatures (approximately 180ºC) to stabilize its dimensions, enhance dye absorption in the subsequent dyeing stage, and remove any potential impurities that the fabric might have brought from the outside.

Stenters, which are used in this pretreatment phase, are also a key piece of machinery in the finishing stage.

This facility is equipped with four stenters, dating from 2001, 2014, 2015, and 2018. The energy sources required for these units include electricity, natural gas, and compressed air.

Image 2. Fabric pretreatment machinery: stenter.

4.2.1.3.2. **Fabric exhaust dyeing (jet technology):**

The visited factory carries out the fabric dyeing process using the jet technology. In these machines, as previously explained, the fabric is in continuous motion inside it, while a series of jets dispense a pressurized mixture of water and dye. These systems require high temperatures, thus the energy sources for this technology include electricity, steam (at around 6 bar), and compressed air [7].

This particular facility is equipped with 27 jet dyeing machines, with ages ranging from 1996 to 2021.

Regarding the temperatures and durations of the dyeing process, the following information was obtained based on the primary fiber of the treated fabric (see table 3):

Table 3. Average dyeing temperatures and durations based on the fabric's predominant fiber.

Title 1	Temperature (ºC)	Duration (h)
Cotton	60	8
Viscose	60	9
Polyester	130	4

The trend observed in Table 3, lower temperatures and longer durations for natural fibers compared to higher temperatures and shorter durations for synthetic fibers, has been corroborated in the other dyeing facilities visited.

The influence of color is also a parameter that has been verified in the dyeing installations. Darker colors generally require higher temperatures and longer dyeing durations.

A challenge observed in studying the influence of colors is that, generally, the visited factories do not have available data on the percentage of dark versus light fabrics dyed in their facilities. Therefore, it is not possible to differentiate the specific consumption of the machines based on this parameter.

Upon completion of the dyeing process, rinsing and washing of the fabrics is performed in the dyeing machines. In this particular facility, the fabrics were washed between 1 and 3 times, depending on factors such as fiber type, colors, etc.

The following images show one of the dyeing machines at this facility during the fabric loading process:

(a) (b)

Image 3. Fabric dyeing machine during the loading process.

The following figures show the interior of these machines, and a descriptive diagram of its functioning:

(a) (b)

Image 4. Fabric dyeing machine pictures; (a) interior of the fabric dyeing machine; (b) descriptive diagram of its functioning.

4.2.1.3.3. Fabric finishing - cold:

Once the dyeing process is completed, the fabric is not only wet but also wrinkled, as shown in the image below, and it is still in a tubular form:

Image 5. Fabric dyeing machine pictures; (a) interior of the fabric dyeing machine; (b) descriptive diagram of its functioning.

The first step is to reopen the fabric tubes (stitched during the mechanical pretreatment phase) to revert them to their original rollable state. This is accomplished using the following machine, which cuts the previously made seam and stretches the fabric:

Image 6. Fabric dyeing machine pictures; (a) interior of the fabric dyeing machine; (b) descriptive diagram of its functioning.

The fabric is fed into the machine from image 6 from the left side of the image, where a motor transports it vertically. A blade located on the left side of the image then cuts the seam. The fabric then moves to the right, where it is stretched and folded.

This machine requires only electricity for its operation. The fabric passes through this machine while still wet.

4.2.1.3.4. Fabric finishing - heat:

The first process to be performed within the hot finishing section is the drying of the fabrics. In this particular facility, this process can be carried out using two different machines: the roller dryer or the tumbler dryer:

The roller dryer, installed in 2007, uses electricity, natural gas, and compressed air as energy sources (see image 7). It consists of a series of heated rollers through which the fabric passes before entering a series of high-temperature chambers. These high temperatures, reaching up to 135°C, are achieved thanks to the natural gas burners (yellow circuit in the following images) installed inside the machine. Depending on the thickness of the fabric, it will move through this system at varying speeds: according to the maintenance team of the visited facility, fabrics passes through the machine at speeds ranging from 7 to 20 meters per minute.

(a) **(b)**

Image 7. Roller dryer machine.

The hot air from within the system is expelled through the chimney shown in Image 8a. Upon completion of the drying process, the fabric is automatically folded at the machine's exit, as shown in image 8b below:

(a) **(b)**

Image 8. Roller dryer machine: (a) fabric folding system; (b) hot air exhaust chimney.

The other machine present at the facility for fabric drying is the tumbler dryer (see image 9). This machine, from 2016, also uses electricity, natural gas, and compressed air. The tumbler dryer serves a dual purpose: in addition to drying, it improves the surface finish of the fabric. This is achieved through the agitation of the fabric within the machinery at elevated temperatures [8]. The temperature reached in this system is approximately 130°C. A schematic diagram of the tumbler dryer is shown in image 9a:

(a) **(b)**

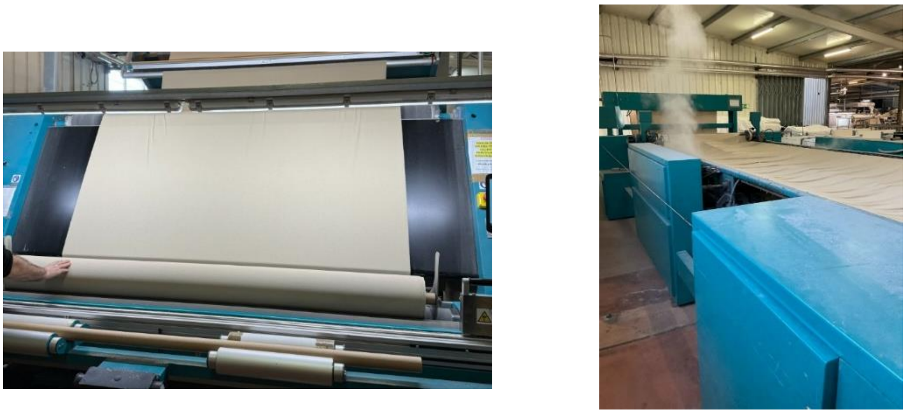
Image 9. Tumbler dryer: (a) tumbler dryer machine; (b) tumbler dryer schematic diagram.

Once the fabric is dried, whether by the roller dryer or the tumbler dryer, it again passes through a stenter, as it did during the pretreatment process.

Stenters are textile machines used to stretch, dry, and provide finishing properties to fabrics. They operate by stretching and heating the fabric through a series of rollers to set its shape and enhance its properties [9].

In this particular facility, the stenters are not used for drying the fabrics but for performing thermofixation processes prior to dyeing and finishing processes after drying. As mentioned earlier, this facility has four stenters. During the finishing process, the required temperature in these systems is 130°C.

Following the stenter, the last machine the fabric passes through before shipment is the Sanfor (image 10). The Sanfor machine is designed to provide dimensional stability to the fabric and set its thickness. The goal of this process is to prevent the fabric from shrinking during washing [10]. It is both a mechanical process, stretching the fabric, and a thermal process, involving the addition of heat through steam. The facility has only one Sanfor, from 2016. The energy sources required for this machine are electricity, steam, and compressed air.



(a) **(b)**

Image 10. Sanfor.

4.2.1.4. Energy efficiency measures:

Several energy efficiency measures were observed in the production machinery, which include:

- Heat Recovery System in Dyeing Machines: the machines are equipped with a heat recovery system that uses the residual heat from the dyeing water to preheat the subsequent water. Information regarding the efficiency of these systems is not available.

- Variable Frequency Drives: both the dyeing machinery and the stenters are equipped with variable frequency drives.

4.2.1.5. Energy sources:

In this section, the total facility's energy consumption is calculated based on the energy sources used. To account for electricity and thermal energy correctly, the following criteria are established:

- Electricity: Recorded in kWh of final electricity.
- Thermal Energy: Recorded in kWh of fuel used. Given that thermal energy is utilized in various forms in the facility, such as hot water, steam, or natural gas directly fed into some machines, all energy sources are standardized and added together this way.

4.2.1.5.1. Thermal energy sources:

4.2.1.5.1.1. District heating

The factory has a direct steam supply from a district heating network connected to a natural gas cogeneration plant. The provided information on the annually purchased steam is as follows:

Table 4. Facility's vapor consumption data from the district heating facility.

Parameter	**Value**
Amount of vapor (ton)	6068
Temperature (ºC)	175
Pressure (bar)	8

Based on this information, the thermal energy used for the generation of this steam is calculated. Thus, for a pressure and temperature of 8 bar and 175ºC (as shown in figure 6, [11]):

$$h_{170º,8\,bar} = 2768{,}3\,\frac{kJ}{kg}$$

$$h_{200º,8\,bar} = 2839{,}8\,\frac{kJ}{kg}$$

And therefore:

$$h_{175º,8\,bar} = 2779{,}4\,\frac{kJ}{kg}$$

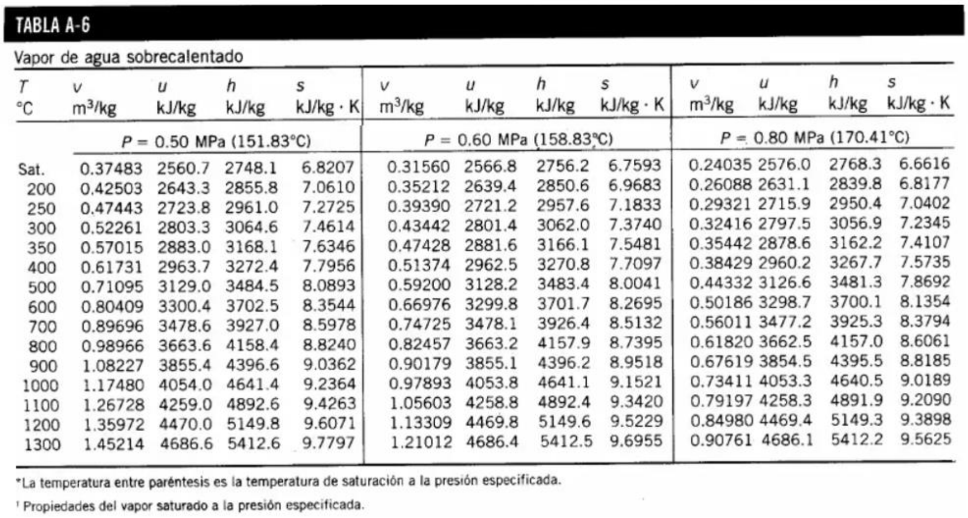


TABLA A-6

Vapor de agua sobrecalentado

T °C	v m^3/kg	u kJ/kg	h kJ/kg	s kJ/kg · K	v m^3/kg	u kJ/kg	h kJ/kg	s kJ/kg · K	v m^3/kg	u kJ/kg	h kJ/kg	s kJ/kg · K
	P = 0.50 MPa (151.83°C)				P = 0.60 MPa (158.83°C)				P = 0.80 MPa (170.41°C)			
Sat.	0.37483	2560.7	2748.1	6.8207	0.31560	2566.8	2756.2	6.7593	0.24035	2576.0	2768.3	6.6616
200	0.42503	2643.3	2855.8	7.0610	0.35212	2639.4	2850.6	6.9683	0.26088	2631.1	2839.8	6.8177
250	0.47443	2723.8	2961.0	7.2725	0.39390	2721.2	2957.6	7.1833	0.29321	2715.9	2950.4	7.0402
300	0.52261	2803.3	3064.6	7.4614	0.43442	2801.4	3062.0	7.3740	0.32416	2797.5	3056.9	7.2345
350	0.57015	2883.0	3168.1	7.6346	0.47428	2881.6	3166.1	7.5481	0.35442	2878.6	3162.2	7.4107
400	0.61731	2963.7	3272.4	7.7956	0.51374	2962.5	3270.8	7.7097	0.38429	2960.2	3267.7	7.5735
500	0.71095	3129.0	3484.5	8.0893	0.59200	3128.2	3483.4	8.0041	0.44332	3126.6	3481.3	7.8692
600	0.80409	3300.4	3702.5	8.3544	0.66976	3299.8	3701.7	8.2695	0.50186	3298.7	3700.1	8.1354
700	0.89696	3478.6	3927.0	8.5978	0.74725	3478.1	3926.4	8.5132	0.56011	3477.2	3925.3	8.3794
800	0.98966	3663.6	4158.4	8.8240	0.82457	3663.2	4157.9	8.7395	0.61820	3662.5	4157.0	8.6061
900	1.08227	3855.4	4396.6	9.0362	0.90179	3855.1	4396.2	8.9518	0.67619	3854.5	4395.5	8.8185
1000	1.17480	4054.0	4641.4	9.2364	0.97893	4053.8	4641.1	9.1521	0.73411	4053.3	4640.5	9.0189
1100	1.26728	4259.0	4892.6	9.4263	1.05603	4258.8	4892.4	9.3420	0.79197	4258.3	4891.9	9.2090
1200	1.35972	4470.0	5149.8	9.6071	1.13309	4469.8	5149.6	9.5229	0.84980	4469.4	5149.3	9.3898
1300	1.45214	4686.6	5412.6	9.7797	1.21012	4686.4	5412.5	9.6955	0.90761	4686.1	5412.2	9.5625

*La temperatura entre paréntesis es la temperatura de saturación a la presión especificada.

[†] Propiedades del vapor saturado a la presión especificada.

Figure 6. Enthalpy tables.

And therefore, the tons of vapor consumed are the following:

$$energy\ contained\ in\ vapor = 6068\ ton * \frac{1000\ kg}{1\ ton} * 2779.4 \frac{kJ}{kg} * \frac{1\ kWh}{3600\ kJ} = 4{,}684{,}833\ kWh$$

Considering the average thermal efficiency of cogeneration systems, the fuel energy used for the generation of this steam is [12,13]:

$$energy\ from\ fuel\ (kWht) = \frac{4{,}684{,}833\ kWh}{0.48} = 9{,}760{,}069\ kWht$$

And the fuel energy that can be assumed to have been dedicated to the generation of thermal energy is:

$$thermal\ energy\ from\ fuel\ (kWht) = 0.57 * 9{,}760{,}069\ = 5{,}563{,}239\ kWht$$

Considering an average loss of 5% in the steam distribution system [14]:

$$thermal\ energy\ from\ fuel\ final\ = \frac{5{,}563{,}239}{0.95} = 5{,}856{,}041\ kWh$$

The amount of thermal energy obtained from the district steam system is 5,856,041 kWh.

4.2.1.5.1.2. Natural Gas

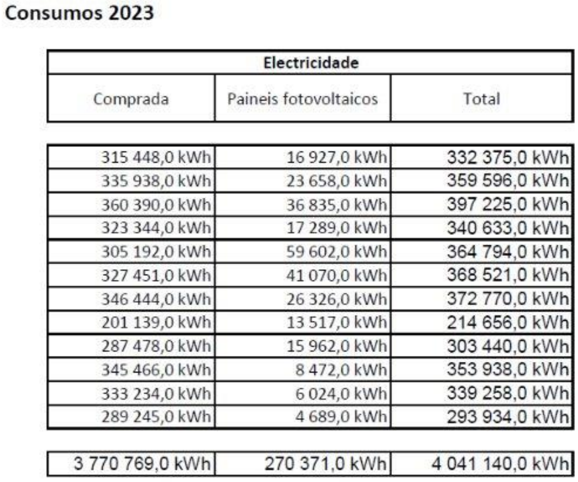
The facility uses natural gas both directly in machinery (stenters) and for steam generation in the boiler. According to the data provided by the facility, the total natural gas consumption amounted to 16,409,712 kWh in 2023.

4.2.1.5.1.3. Sustainable Forest Biomass

The facility also consumes pellets sourced from a sustainable forest. The annual consumption of pellets in 2023 was 179.54 tons, equivalent to 810,982.2 kWh. This represents a calorific value for the biomass of 4.517 kWh/kg. This falls within the expected range according to various references [15][16].

4.2.1.5.2. Electricity sources:

The facility sources its electricity from two main origins: the electricity grid and an on-site photovoltaic solar installation. According to the facility, the total electrical consumption is distributed as detailed in figure 7:



Consumos 2023

Electricidade		
Comprada	Paineis fotovoltaicos	Total
315 448,0 kWh	16 927,0 kWh	332 375,0 kWh
335 938,0 kWh	23 658,0 kWh	359 596,0 kWh
360 390,0 kWh	36 835,0 kWh	397 225,0 kWh
323 344,0 kWh	17 289,0 kWh	340 633,0 kWh
305 192,0 kWh	59 602,0 kWh	364 794,0 kWh
327 451,0 kWh	41 070,0 kWh	368 521,0 kWh
346 444,0 kWh	26 326,0 kWh	372 770,0 kWh
201 139,0 kWh	13 517,0 kWh	214 656,0 kWh
287 478,0 kWh	15 962,0 kWh	303 440,0 kWh
345 466,0 kWh	8 472,0 kWh	353 938,0 kWh
333 234,0 kWh	6 024,0 kWh	339 258,0 kWh
289 245,0 kWh	4 689,0 kWh	293 934,0 kWh
3 770 769,0 kWh	270 371,0 kWh	4 041 140,0 kWh

Figure 7. Grid electricity consumption and solar PV self-consumption of electricity for the year 2023.

This way, it can be inferred:

- **Grid Electricity**: 3,770 MWh
- **Photovoltaic Solar Electricity**: 270.34 MWh

4.2.1.5.2.1. Purchase of green certificates:

The facility also acquires green energy certificates to offset its emissions associated with electricity consumption from the grid. The quantity of green attributes, or Energy Attribute Certificates (EACs), purchased by the facility in 2023 amounts to an equivalent of 4,055,000 kWh.

4.2.1.5.3. Total thermal energy consumption:

Considering all the mentioned facility's thermal energy sources, the total thermal energy consumed by the facility, understood as the energy contained in the fuels used, is:

$$thermal\ energy\ consumption\ (kWh) = district\ heating + natural\ gas + biomass$$

$$thermal\ energy\ consumption\ (kWh) = 5{,}856{,}041\ +\ 16{,}409{,}712 + 810{,}982 = 23{,}076{,}735\ kWh$$

4.2.1.5.4. Total electrical energy consumption:

Regarding electricity consumption:

$$electricity\ consumption\ (kWh) = solar\ PV + electric\ grid$$

$$electricity\ consumption\ (kWh) = 270{,}371 + 3{,}770{,}769 = 4{,}041{,}140\ kWh$$

4.2.1.5.5. Energy distribution within the processes present in the factory:

Based on the total thermal and electrical energy consumption values for the factory, the corresponding percentage of energy consumption must be allocated to the different production processes carried out in the facility. As detailed further, the facility does not have measurement devices for electricity or thermal energy at the process level. However, based on experience, the facility's team defined the following distribution among the different processes. Given the annual production of the factory (2,572,232 kilograms), specific consumption for each production process is calculated as follows:

Table 5. Specific electric and thermal energy consumption per production process in the facility.

	Electricity			Thermal energy		
	%	Total (kWh)	KPI (kWh/kg)	%	Total (kWh)	KPI (kWh/kg)
Pretreatment	10	404.114	0,16	5	1.153.837	0,45
Dyeing	32	1.311.838	0,51	35	8.051.086	3,13
Cold finishes	5	202.057	0,08	0	0	0
Hot finishes	53	2.123.131	0,83	60	13.871.812	5,38

4.2.1.6. Auxiliary machinery:

This section provides a brief description of the auxiliary machinery present in the facility. Although these components are not directly involved in the textile production process, they are essential for its proper operation. The facility includes:

- Two Air Compressors: these compressors supply the compressed air required for various pneumatic systems and machinery within the facility.
- Two Steam Boilers: these boilers generate the steam needed for several production processes, including dyeing and finishing.
- Power Factor Correction Bank: this equipment is used to correct the power factor of the facility’s electrical system, enhancing energy efficiency.

4.2.1.6.1. Compressors:

The facility is equipped with two BOGE compressors, model SLF 75-3, from the years 2014 and 2016. Both compressors are variable. Their operation is alternate to avoid overloading either unit and to ensure a continuous supply of compressed air, given the facility's uninterrupted production schedule from Monday to Friday.

The compressors compress air to approximately 7 bar of pressure, while the machinery demands it at around 6 bar. This difference is attributed to losses in the distribution system.

According to the facility staff, there is a written procedure for inspecting compressed air leaks. However, these inspections are conducted visually and audibly; no leak detectors or thermal cameras are used.

To reduce the temperature of the intake air, the compressors draw air from the outside. The frequency of filter replacements is not documented.

In addition to the two compressors, the facility has two compressed air dryers (see Image 11b) to remove moisture from the air, as well as an air receiver tank.

(a) **(b)**

Image 11. Compressed Air system elements: (a) Compressor; (b) Compressed Air dryers.

4.2.1.6.2. Boilers:

The facility is equipped with two boilers: one biomass boiler (1998) (see image 12a) and one natural gas boiler (1994) (see image 12b). Both are used for steam generation during peak consumption periods. Typically, steam is supplied by the district heating network, and the boilers remain inactive. The decision to use one boiler or the other, when necessary, is made during the production planning meeting, approximately one week in advance, based on economic criteria (depending on current gas and biomass prices).

The steam is distributed at a pressure of 6 bars. It is noteworthy that the biomass boiler is equipped with an economizer, while the natural gas boiler is not.

The steam distribution system has the capability to recover condensates. The water entering the boilers undergoes chemical treatment and descaling.

(a) **(b)**

Image 11. Boilers: (a) Biomass boiler; (b) Natural Gas boiler.

4.2.1.6.3. Maintenance and operation:

In general, the maintenance team at the facility, consisting of three members, performs preventive maintenance on all equipment. They also handle cleaning tasks for the machinery.

The modern pieces of equipment are covered by maintenance programs conducted by their respective manufacturers.

4.2.1.7. Energy efficiency rating:

Upon completion of the visit and based on the collected information, the facility is evaluated on various aspects related to equipment age, operational mode, maintenance frequency, and other factors.

4.2.1.7.1. Production machinery age: score of 4 out of 5.

The processes with the highest energy consumption in the facility are dyeing and heat finishing of fabrics. The machinery for these processes is relatively modern, with ages ranging approximately between 5 and 15 years, and some even less than 2 years.

4.2.1.7.2. Auxiliary machinery age: score of 3 out 5.

The boilers date back to 1994 and 1998, although most of the steam is currently sourced from the district steam network (or offsite cogeneration). The air compressors are from 2014 and 2016.

4.2.1.7.3. Maintenance practices: score of 3 out of 5

In general, preventive maintenance is regularly carried out on all equipment in the facility. However, it is not specified that this maintenance is conducted according to the manufacturer's recommendations.

4.2.1.7.4. Mode of operation of production equipment: score of 4 out of 5

Most of the processes are automatically controlled.

4.2.1.7.5. Mode of operation of auxiliary equipment: score of 4 out of 5

The gas boiler is equipped with modulating burners, and the biomass boiler's feeding system is automatic. Additionally, the compressors are integrated and both are variable.

4.2.1.7.6. Process variable monitoring: score of 3 out of 5

Most of the production machinery elements are equipped with displays or screens that show their process variables. However, generally, the operation of the various equipment is not integrated with each other.

4.2.1.7.7. Commitment with continuous improvement: score of 4 out of 5

The facility has the following notable energy efficiency measures: heat recovery in the dyeing process, heat recovery in the stenters, biomass combustion to reduce non-renewable primary energy consumption, installation of photovoltaic panels, acquisition of batteries for storing energy outside of production hours (these were in the process of installation at the time of the visit), and LED lighting.

4.2.1.7.8. Level of energy consumption submetering: score of 2 out of 5

Currently, the facility has, in addition to total consumption invoices, sub-metering of the facility's total electrical consumption through the photovoltaic solar installation program.

4.3. Establishment of energy objectives:

Upon completing the audit program, the information obtained is processed and analyzed to establish the optimal energy consumption for the fabric exhaust dyeing process (in kWh electrical/kg and kWh thermal/kg). This optimal energy consumption value will be subsequently used to calculate the optimal energy consumption for any given installation that carries out this process.

Example Application of KPIs:

If it were established, for example, that the optimal energy consumption for the Fabric Exhaust Dyeing process is as follows:

- Optimal Electrical Consumption KPI: 2.5 kWh/kg
- Optimal Thermal Consumption KPI: 4.8 kWh/kg

For a factory carrying out such process with an annual production of 10,000 kg, its optimal energy consumption would be:

$$optimal\ electricity\ consumption = 2{,}5\frac{kWh}{kg} * 10.000\ kg = 25.000\ kWh$$

$$thermal\ energy\ optimal\ consumption = 4{,}8\frac{kWh}{kg} * 10.000\ kg = 48.000\ kWh$$

If the factory's energy consumption exceeded these values, it would need to implement a series of energy efficiency measures in its processes to reduce its consumption and reach the objective set.

4.3.1. Data collected from the Fabric Exhaust Dyeing factories:

The specific consumptions or KPIs for electrical and thermal consumption, as well as the energy efficiency rating of the visited factories carrying out the Fabric Exhaust Dyeing process are shown below, in table 6:

The electrical KPI refers to the specific electrical consumption of the dyeing process (in kWh/kg), and the thermal KPI refers to the specific thermal consumption of the dyeing process (in kWh/kg).

During the audit phase, 19 factories performing Fabric Exhaust Dyeing were visited:

Table 6. Specific electric and thermal energy consumption, and rating, of the visited facilities.

Facilities	Electric KPI (kWh/kg)	Thermal KPI (kWh/kg)	Rating
BG_018	1,02	8,01	5,1
CH_003	0,47	5,36	7,1
CH_004	0,39	3,67	6,3
CH_008	0,23	0,29	6,5
CH_013	0,94	9,22	6,2
CH_014	0,18	1,18	7,7
CH_022	0,18	0,00	6,5
IN_019	0,80	5,34	7,3
IN_026	0,31	9,14	5,1
IT_005	0,83	3,09	7
PT_008	0,51	3,13	6,8
PT_009	0,31	2,96	8,2
PT_020	0,44	3,23	8,4
PT_025	0,50	5,45	4,9
SP_003	0,58	8,50	6,3
SP_006	0,40	3,14	4,6
SP_012	0,62	6,77	2,8
TR_015	0,64	9,32	3
TR_021	0,66	1,20	5

For the specific Fabric Exhaust Dyeing process, apart from the variables mentioned in the previous section of this article, the following information was collected through the questionnaire:

- Type of Dyeing Process: Jet, beck/winch, or jigger.
- Machinery age.
- Energy Sources.
- Type of Fibers Used: temperature and duration of the process.
- Pre-treatment Process Prior to Dyeing.
- Post-dyeing Finishing Process.
- Liquor Ratio: ratio of water to fabric in the dye bath.
- Fabric grammage: thickness, measured in grams per square meter.
- Rating: Assigned based on collected information, encompassing factors such as machinery age, maintenance practices, the level of detail in energy consumption measures, etc.

The objective of the study, as it has been mentioned before in this article, is to understand how the energy consumption of the Fabric Exhaust Dyeing process is affected by these variables.

Although all this information was requested during the audits, factories were not always able to provide all these data, as the representatives receiving the Arup team often had managerial rather than technical roles and were unfamiliar with specific process parameters.

The data collected for all the variables above for the analyzed sample of 19 factories can be found in Appendix A.

The collected information is now analyzed, per variable:

4.3.1.1. Type of exhaust dyeing process:

In the figure below (figure 8), the relationship between electrical consumption (Electrical KPI, X-axis) and thermal consumption (Thermal KPI, Y-axis) is shown for each combination of dyeing technologies in the visited factories. Each point represents a factory.

As it can be observed, the technology with the largest data set is the "Jets" technology (in dark blue, 10 points). For factories with "Jet," "Jigger," and "Jet and Jigger" dyeing types, represented in dark blue, purple, and orange, respectively, there is no clear trend indicating higher or lower energy consumption based on the employed technology. The "Beck/Winch" dyeing type does seem to have somewhat higher energy consumption, although the study sample for this type is relatively small compared to the other dyeing types (only 3 points, represented in light blue).

According to the literature, the least energy-intensive process should be the "Jigger," followed by the "Jet," and finally the "Beck/Winch," thus the higher consumptions observed for this type of technology would be justified [17].

It is also noteworthy that, in general, thermal and electrical consumption values exhibit a linear relationship, as higher electrical consumption values also correspond to higher thermal consumption values.

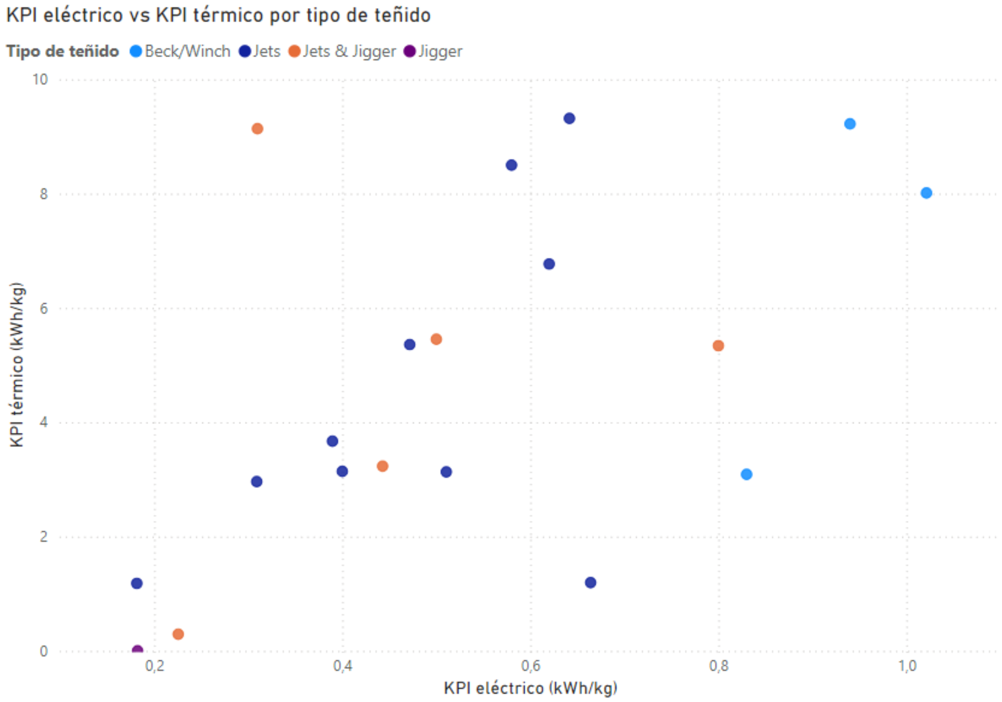


Figure 8. Electric and thermal KPI by type of dyeing process.

4.3.1.2. Machinery age:

The age of the machinery is another key characteristic identified as crucial in the energy consumption of the equipment.

In Figure 9 below, the electrical and thermal consumption of the facilities (each represented by a point) is shown as a function of the machinery age.

Regarding thermal energy consumption, represented on the Y-axis, it is observed that machinery with an age of less than 15 years (in green and yellow) generally exhibits lower specific consumption than machinery aged between 15 and 25 years (orange), and machinery older than 25 years (blue).

For electrical consumption, represented on the X-axis, although less pronounced, the aforementioned trend can also be observed:

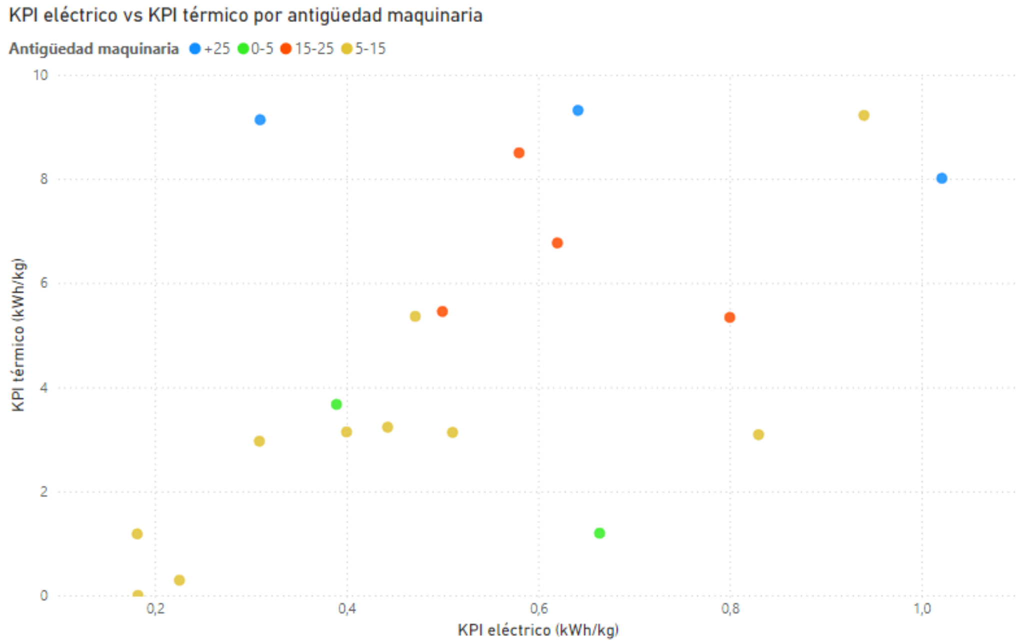


Figure 9. Electric and thermal KPI by production equipment age.

This phenomenon generally occurs for each of the dyeing types studied, as can be seen in the figures below:

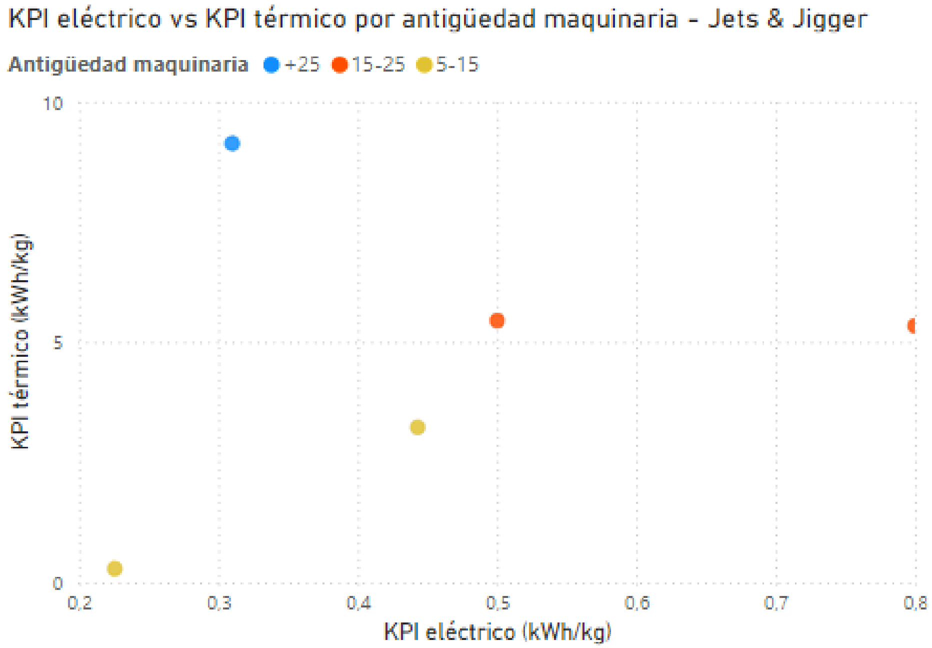


Figure 10. Electric and thermal KPI by production equipment age for the Jets and Jigger technology.

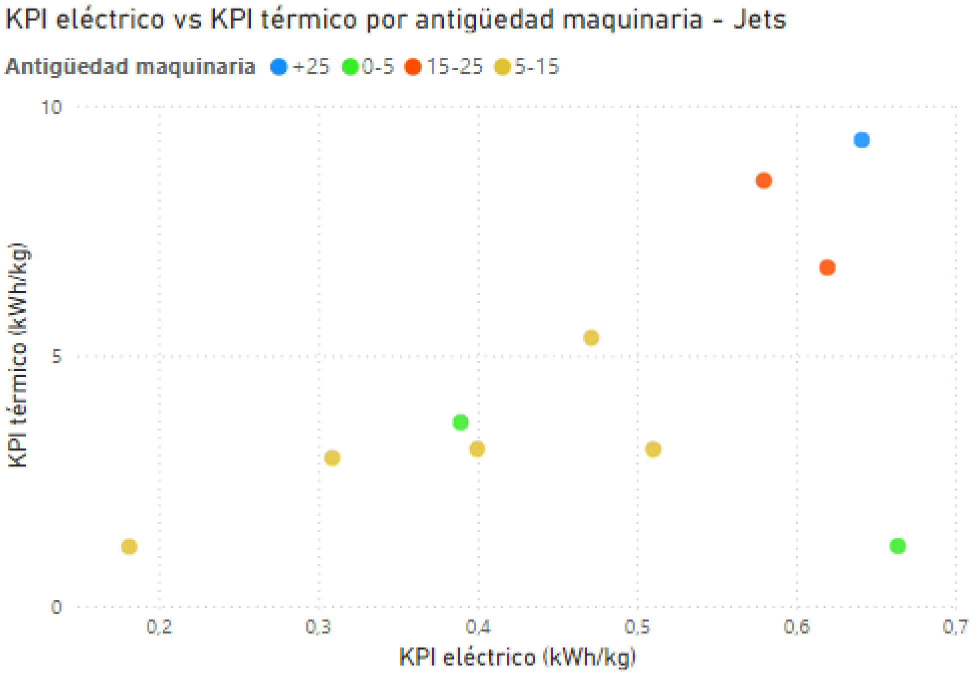


Figure 11. Electric and thermal KPI by production equipment age for the Jets technology.

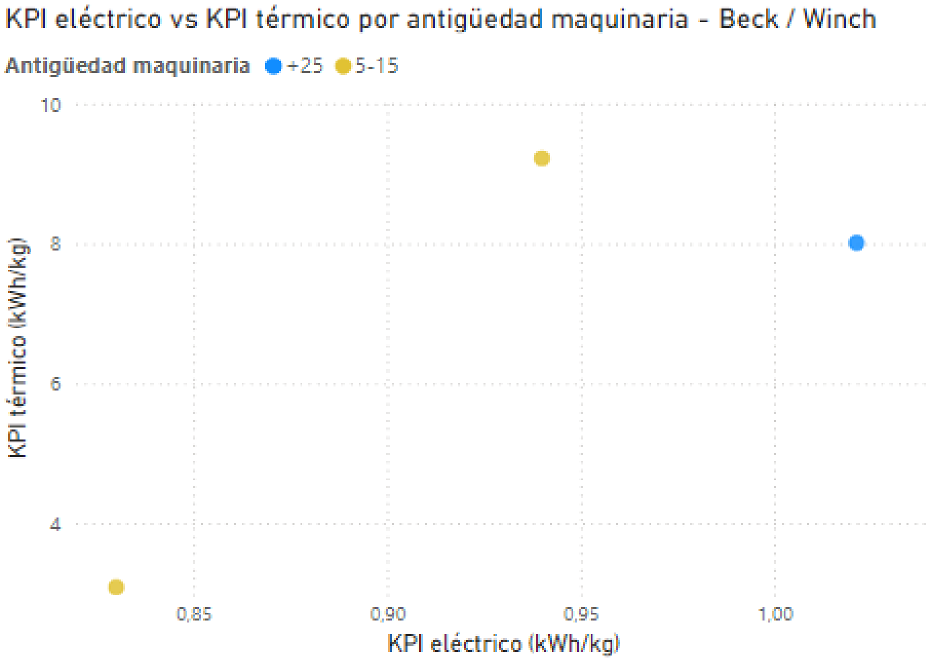


Figure 12. Electric and thermal KPI by production equipment age for the Beck/Winch technology

4.3.1.3. Process source of energy:

This variable becomes particularly important in cases where the source of thermal energy used might be electricity (for example, in ironing processes, it is common to obtain steam by heating water with an electric boiler or from the installation's own steam distribution system). In such cases, significant differences are observed in the KPIs of electrical and thermal consumption based on the source of steam used.

In the case of the batch fabric dyeing process, the primary energy sources are electricity, compressed air, and steam. These are the energy sources used in the analyzed sample, as can be seen in Appendix A.

4.3.1.4. Type of fibers used:

In the following figures, the values of electrical KPIs (left) and thermal KPIs (right) are shown as a function of the percentage of natural fibers (versus synthetic fibers) processed for each of the three studied technologies.

In the case of the Jets technology: it can be observed that factories with a higher predominance of synthetic fibers (lower values on the X-axis) exhibit higher energy consumptions (both thermal and electrical) compared to those working with a higher percentage of natural fibers (Figure 13).

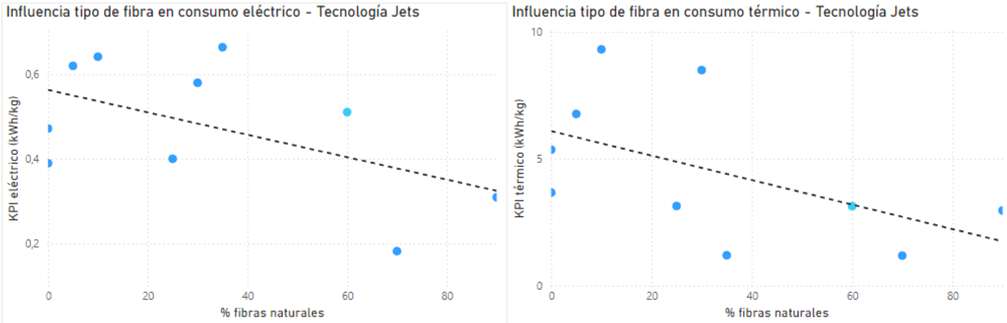


Figure 13. Electric and thermal KPI based on the percentage of natural fibers for Jet technology

This trend has not been observed for the other technologies, where the influence of the type of fiber used is indeterminate. It should be noted that the number of measurements for these sets is limited, which complicates drawing reliable conclusions.

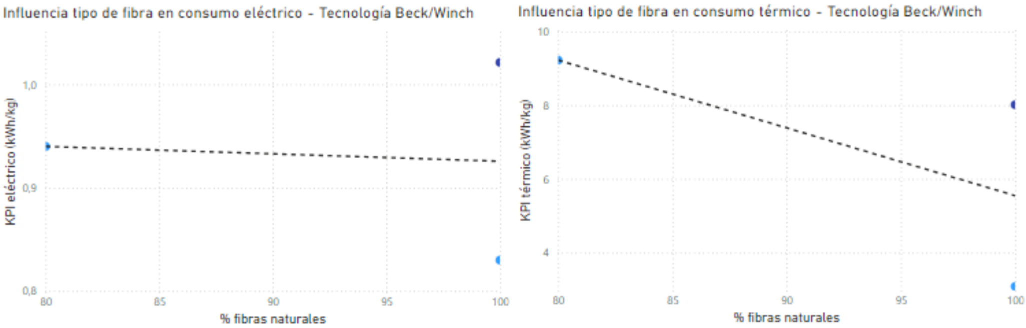


Figure 14. Electric and thermal KPI based on the percentage of natural fibers Beck/Winch Jet technology

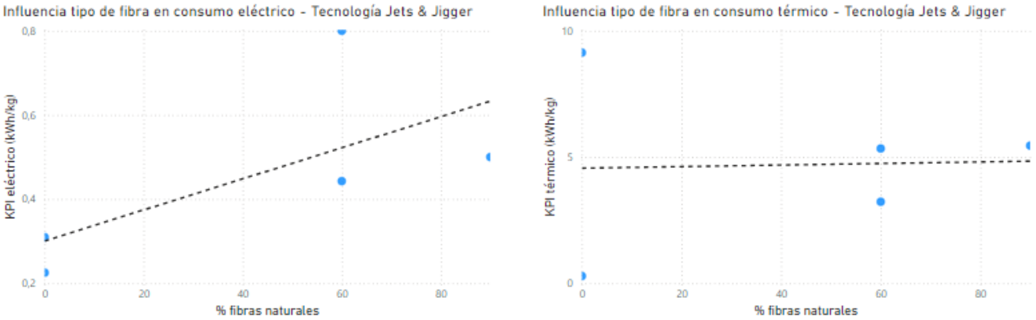


Figure 13. Electric and thermal KPI based on the percentage of natural fibers for Jets & Jigger technology

In general, as previously mentioned, natural fibers require lower temperatures and longer process durations, while synthetic fibers behave oppositely [18][19].

This phenomenon is observed for the Jets dyeing data (for the other dyeing types, there are not enough data to conduct the study).

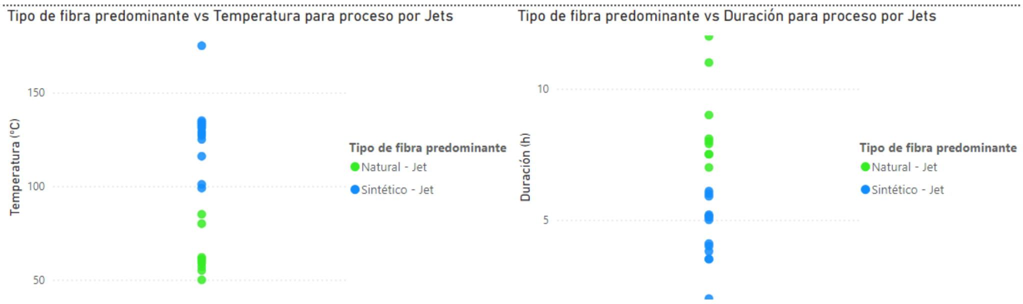


Figure 14. Fabric dyeing temperature and durations for natural and synthetic fibers

4.3.1.4. Pretreatment prior to washing and post-washing finishing processes:

Pre-treatment and finishing processes, both prior to and after washing, are carried out within the dyeing machinery. These processes involve the addition of various products to enhance color adherence to the fabrics.

Regarding the pre-treatment variable, it is observed that, on average, factories that perform pre-treatment before dyeing exhibit slightly higher electrical and thermal consumption (see Figure 15). Although the difference is not particularly notable, it can be estimated that, in general, the points representing pre-treatment (in green) are, on average, further from zero compared to those without pre-treatment (in red), especially on the thermal consumption axis.

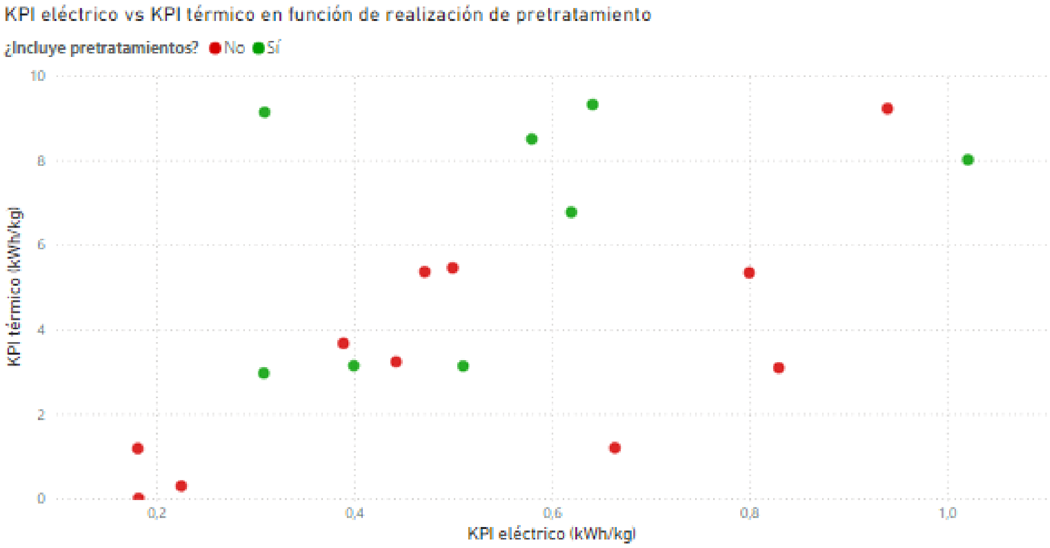


Figure 15. Electric and thermal KPI based on the inclusion of a pretreatment process

This detail is even more pronounced when the same comparison is graphed specifically for Jets dyeing (see Figure 16):

Figure 16. Electric and thermal KPI based on the inclusion of a pretreatment process for Jets technology

However, the same trend is not observed for the variable related to the implementation of finishing processes (see Figure 17):

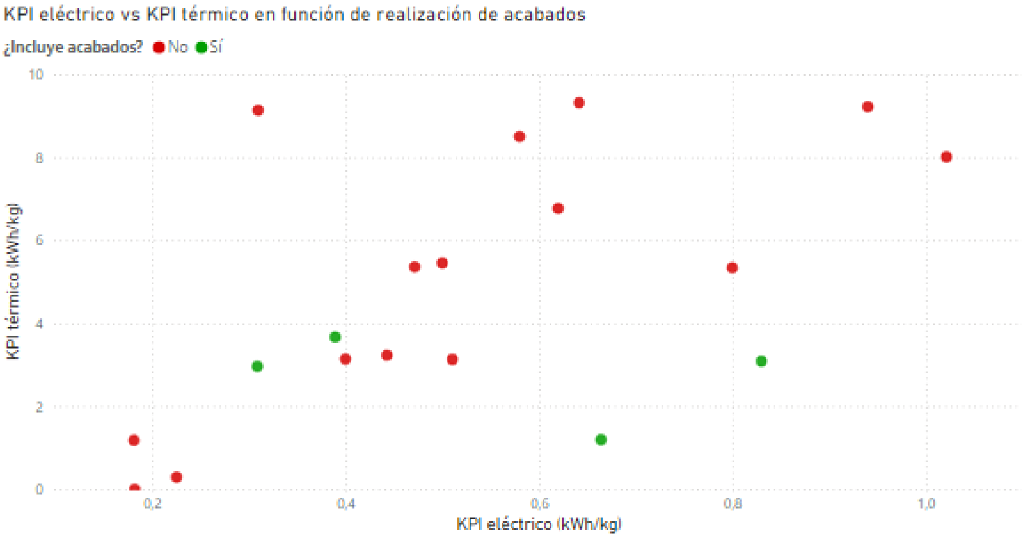


Figure 17. Electric and thermal KPI based on the inclusion of a finishing process

This circumstance does not, at first glance, have a logical justification. However, a justification is found when examining the age of the equipment used for finishing processes: only 4 installations perform post-washing finishing, and these 4 installations have ages ranging from 0 to 5 years in two cases and from 5 to 15 years in the other two.

It can thus be concluded that the additional consumption due to finishing processes is offset by the higher efficiency of the more recent machinery, which incorporates the latest and most efficient technology.

4.3.1.5. Liquor ratio:

The "liquor ratio" can be defined as the volume of water and dye in relation to the weight of the fabric. It is expressed as 1:X, where 1 represents the proportion corresponding to the fabric, and X denotes the volume of water and dye in the bath.

Higher values of X correspond to a greater amount of water used in the dyeing process, and consequently, a higher energy consumption for the textile process.

For the analyzed sample, it is observed that the liquor ratios used vary depending on the type of technology (see Table 7).

Table 7. Observed liquor ratios based on the type of exhaust dyeing process analyzed.

Type of technology	Liquor ratio range	Number of facilities
Jet	1:4 – 1:10	18
Jigger	1:1 – 1:6	4
Beck/Winch	1:6 – 1:20	3

Preliminarily, it can be concluded that the Jigger technology employs the lowest ratios, followed by the Jet, and finally the Winch. These conclusions are supported by the literature [20].

In the case of dyeing with Jets, it is evident that as the liquor ratio increases (represented on the X-axis of Figure 18), the energy consumption of the process also increases (Y-axis).

However, due to the limited number of data for the Jigger and Winch technologies, it is preferable not to draw conclusions in this regard.

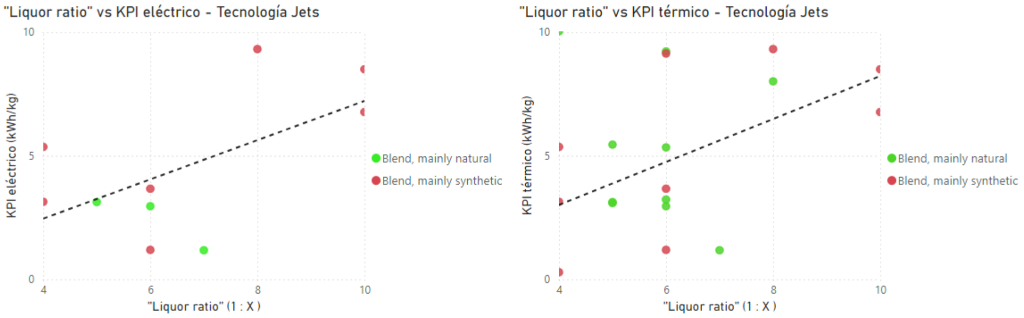


Figure 18. Electric and thermal KPI based on the dyeing liquor ratio for jet dyeing.

No significant differences are observed in the liquor ratio based on whether natural or synthetic fibers are used.

4.3.1.6. Grammage:

The variable of fabric weight (grammage) could not be studied due to the low number of data points obtained from the analyzed sample. It is expected that higher fabric weight would correspond to greater energy consumption in the dyeing process.

4.3.1.7. Rating:

Finally, the influence of the studied parameters, as well as other factors such as maintenance levels and operational modes of the machinery, is observed by examining the relationship between energy consumption KPIs and the rating or classification of each facility.

In the graphs presented in Figure 19, the electrical and thermal KPIs of the facilities (Y-axis) are plotted against the rating or classification of these facilities (X-axis). In general, the trend line for energy consumption decreases as the overall rating of the facility increases.

This phenomenon is even more pronounced when excluding the two points located furthest to the left in the graphs. These two facilities are clearly outliers in terms of facility ratings, as they are significantly distant from the cluster of points representing the remaining factories.

By plotting a trend line that excludes these two values (in green), the inverse relationship between rating and energy consumption becomes considerably more pronounced.

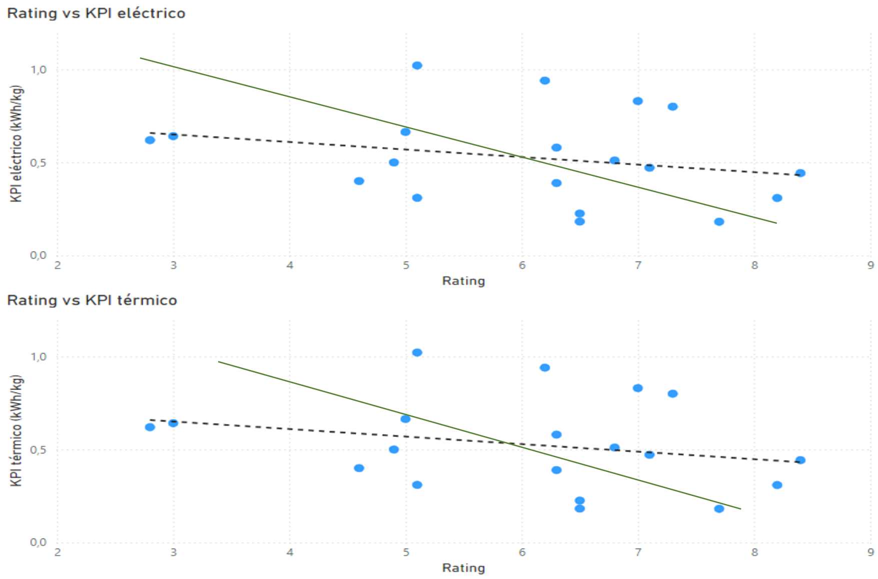


Figure 19. Electric and thermal KPI based on the facility's rating.

5. Results

The following conclusions can be drawn from the study previously performed:

- Type of Dyeing:

No conclusive results were obtained regarding the influence of dyeing type on the energy consumption of the process. An increased sample size of factories using "Jigger" and "Beck/Winch" processes is necessary to establish conclusions in this regard. The most common technology appears to be "Jet," based on the studied sample. This makes sense as it is the most modern and efficient technology.

- Age of Machinery

Significant differences in energy consumption (both electrical and thermal) were observed based on the age ranges of the machinery. However, no significant differences in consumption were noted between the 0-5 and 5-15 year ranges. This may suggest the need to discretize machinery into other age brackets (e.g., 0-10, 10-15, 15-25, +25 years) where a greater difference in energy consumption can be observed.

- Energy Source of the Process

The analyzed process always uses the same energy sources. Therefore, this variable does not appear to influence the "Exhaust Dyeing" process group.

- Type of Fibers Used

Natural fibers require lower temperatures but longer dyeing durations compared to synthetic fibers, which require higher temperatures and shorter durations. It was observed that for the Jet dyeing process, synthetic fabrics require higher inputs of electrical and thermal energy than natural ones. This trend was not observed for the other two types of dyeing due to the sample size being too small to draw conclusions.

- Pre-treatment Before Dyeing

Processes that include pre-treatment generally have higher energy consumption, especially thermal.

- Post-dyeing Finishing Process

Contrary to expectations, factories that perform the finishing process after dyeing have lower energy consumption than others. The explanation found is that the machinery used in these cases is relatively new.

- Liquor Ratio (Ratio of Water to Fabric in the Dye Bath)

Higher liquor ratios lead to higher energy consumption. Preliminary results indicate that Jigger dyeing has the lowest liquor ratios, followed by Jet and Winch. No differences in liquor ratio were observed based on the type of fiber used. A direct relationship between higher liquor ratios and increased energy consumption was observed for the Jet technology.

- Fabric Weight

This variable could not be studied due to the lack of available data. According to the literature, higher fabric weights would be expected to correlate with higher energy consumption.

- Rating

It can be observed that as the Rating of the facilities increases, their energy consumption decreases. This confirms the influence of not only the variables studied in this section but also the other variables that make up the Rating, such as maintenance practices and the mode of operation of the equipment.

Considering all the above, the only variable that will determine the optimal KPI for electrical and thermal consumption of the fabric dyeing process will be the type of fiber used. Ideally, the optimal KPI should also differ based on the type of dyeing performed (jet, jigger, winch). However, due to the current lack of sufficient information on independent jigger and winch processes, only a generic KPI will be established based on the results for Jet technology.

5.1. KPI establishment:

As mentioned in the previous paragraph, since significant differences in energy consumption have been observed in the dyeing process based on the main fiber type of the fabric, two sets of target KPIs for electrical and thermal consumption will be established.

To set these values, the results obtained for natural and synthetic fibers are studied separately.

5.1.1. KPI establishment for exhaust dyeing of fabrics with natural fibers (with Jet technology):

The purpose of setting these KPIs is to define an energy consumption target, both electrical and thermal, that will allow for the reduction of energy consumption in the processes and that, at the same time:

- Is technically achievable by the majority of factories.
- Ensures a considerable reduction in energy consumption when factories reach this consumption target.

Preliminarily, setting this energy consumption target at the first quartile of the consumption values of the analyzed factories is proposed.

Thus, for the analyzed factories using jet dyeing technology and predominantly natural fibers, the first quartile values for their electrical and thermal consumption are calculated (Table 8).

Table 8. Electric and thermal KPIs, and target definition for natural fabric exhaust dyeing.

	Electric KPI (kWh/kg)	**Thermal KPI (kWh/kg)**	**Rating**	**Equipment age**
CH_014	0.18	1.18	7.7	5-15
IN_019	0.80	5.34	7.3	15-25
PT_008	0.51	3.13	6.8	5-15
PT_009	0.31	2.96	8.2	5-15
PT_020	0.44	3.23	8.4	5-15
PT_025	0.50	5.45	4.9	15-25
Q1 (objective KPI)	0.34	3.00		

The technical feasibility of the preliminarily established energy consumption targets (0.34 kWh electrical/kg; 3 kWh thermal/kg) is validated through the following three checks:

- Validation Test 1: Factory Ratings Analysis

The first validation test involves analyzing the ratings of the studied factories that already meet the proposed emission targets (Table 9).

Table 9. Electric and thermal KPIs, and target definition for natural fabric exhaust dyeing. Validation test 1

	Electric KPI (kWh/kg)	Thermal KPI (kWh/kg)	Rating	Equipment age
CH_014	0.18	1.18	7.7	5-15
IN_019	0.80	5.34	7.3	15-25
PT_008	0.51	3.13	6.8	5-15
PT_009	0.31	2.96	8.2	5-15
PT_020	0.44	3.23	8.4	5-15
PT_025	0.50	5.45	4.9	15-25
Q1 (objective KPI)	**0.34**	**3.00**		

The average ratings of the facilities with jet dyeing processes is 7.2, while the ratings of the facilities currently meeting the targets are 7.7 and 8.2 points. Given that these values are not excessively high compared to the overall average (7% higher and 13% higher respectively), it is understood that the other facilities should be able to achieve the proposed target by implementing energy efficiency measures.

- Validation Test 2:

Validation Test 2 involves comparing the target KPI with the average KPIs of the facilities grouped by age (Table 10).

Table 10. Target definition for natural fabric exhaust dyeing. Validation test 2

	Electric KPI (kWh/kg)	Thermal KPI (kWh/kg)
Quartile 1 (objective KPI)	0,34	3,00
Average consumption for facilities with ages between 5-15	0,36	2,63
Average consumption for facilities with ages between 15-25	0,65	5,40

However, as can be seen, on average, factories with equipment less than 15 years old easily meet the established thermal consumption KPI and are very close to meeting the electrical consumption KPI (an additional average reduction of just 5% in electrical consumption would be required). This implies that, in general, with relatively recent equipment or, alternatively, with the implementation of energy efficiency measures to update current equipment, the target KPI would be achievable.

- Validation Test 3:

The proposed consumption targets fall within the expected energy consumption ranges according to the studied literature. According to the literature, the electrical consumption of jet processes could range from 0.24 to 4.4 kWh/kg, with the optimal consumption KPI defined within this range. For thermal consumption, the literature reported an average thermal consumption between 1.3 and 7.3 kWh/kg, with the defined KPI also within this range.

The second objective of establishing the KPI is that achieving this consumption target should lead to a significant reduction in the energy consumption of the processes.

If all analyzed factories reduced their consumption to meet the target consumption, and those currently consuming less than the target maintained their consumption levels, the total energy consumption of the fabric dyeing process would decrease by 25% in electrical consumption and 15% in thermal consumption (see Table 11).

Table 11. Average consumption reduction for natural fabric exhaust dyeing process.

	Electric KPI (kWh/kg)	Thermal KPI (kWh/kg)
CH_014	0.18	1.18
IN_019	0.80	5.34
PT_008	0.51	3.13
PT_009	0.31	2.96
PT_020	0.44	3.23
PT_025	0.50	5.45
Average specific consumption (kWh/kg)	**0,46**	**3,55**
Target consumption (KPI)	**0,34**	**3,00**
Average consumption reduction	**25%**	**15%**

Considering the emission reduction targets of major companies in the sector for the coming years, a 25% reduction in electrical consumption and a 15% reduction in thermal consumption for the highly energy-intensive fabric dyeing process is a significant achievement.

5.1.2. KPI establishment for exhaust dyeing of fabrics with synthetic fibers (with Jet technology):

The same procedure described for natural fibers is applied to determine the target KPIs for synthetic fabric dyeing processes. In this case, the data used for the analysis are as follows (Table 12):

Table 12. Electric and thermal KPIs, and target definition for synthetic fabric exhaust dyeing.

	Electric KPI (kWh/kg)	Thermal KPI (kWh/kg)	Rating	Equipment age
CH_003	0.47	5.36	7.1	5-15
CH_004	0.39	3.67	6.3	0-5
CH_008	0.23	0.29	6.5	5-15
IN_026	0.31	9.14	5.1	+25
SP_003	0.58	8.50	6.3	15-25
SP_006	0.40	3.14	4.6	5-15
SP_012	0.62	6.77	2.8	15-25
TR_015	0.64	9.32	3	+25
TR_021	0.66	1.20	5	0-5
Q1 (objective KPI)	0.39	3.14		

Regarding the technical feasibility analysis of the preliminary results:

- Validation Test 1: Factory Ratings Analysis

In this validation test, the specific consumptions of the factories that currently meet the defined target KPI are compared with their respective ratings:

Table 13. Electric and thermal KPIs, and target definition for synthetic fabric exhaust dyeing. Validation test 1.

	Electric KPI (kWh/kg)	Thermal KPI (kWh/kg)	Rating	Equipment age
CH_003	0.47	5.36	7.1	5-15
CH_004	0.39	3.67	6.3	0-5
CH_008	0.23	0.29	6.5	5-15
IN_026	0.31	9.14	5.1	+25
SP_003	0.58	8.50	6.3	15-25
SP_006	0.40	3.14	4.6	5-15
SP_012	0.62	6.77	2.8	15-25
TR_015	0.64	9.32	3	+25
TR_021	0.66	1.20	5	0-5
Q1 (objective KPI)	0.39	3.14		

The ratings of the facilities that meet one or both of the target KPIs are around a score of 5 to 6. On the other hand, the average rating of this set of factories is 5.26. This suggests that high efforts are not required to achieve the target KPIs, and therefore the defined objectives also pass this validation test.

- Validation Test 2:

Validation Test 2: In this case, the target KPIs are compared with the average specific consumption of the studied factories based on their age.

Table 14. Target definition for synthetic fabric exhaust dyeing. Validation test 2

	Electric KPI (kWh/kg)	Thermal KPI (kWh/kg)
Quartile 1 (objective KPI)	0,39	3,14
Average consumption for facilities with ages between 0-15	0,43	2,73
Average consumption for facilities with ages between 15-25	0,60	7,64
Average consumption for facilities with ages +25	0,48	9,23

Regarding specific thermal consumption, factories with equipment less than 15 years old, on average, meet the established target. In terms of electrical consumption, they are close to the target but would require an additional average reduction of 10%. Considering the generally low ratings of these installations, it is assumed that newer factories could easily reach the proposed target through the implementation of energy efficiency measures. Older factories will need to improve their energy efficiency performance or partially renew their equipment to achieve the proposed target.

- Validation Test 3:

The proposed consumption targets also fall within the expected energy consumption ranges according to the literature reviewed.

For the case of synthetic fabrics, regarding the objective of a substantial reduction in energy consumption (Table 15):

Table 15. Average consumption reduction for synthetic fabric exhaust dyeing process.

	Electric KPI (kWh/kg)	Thermal KPI (kWh/kg)
CH_003	0,47	5,36
CH_004	0,39	3,67
CH_008	0,23	0,29
IN_026	0,31	9,14
SP_003	0,58	8,50
SP_006	0,40	3,14
SP_012	0,62	6,77
TR_015	0,64	9,32
TR_021	0,66	1,20
Average specific consumption (kWh/kg)	**0,48**	**5,26**
Target consumption (KPI)	**0,39**	**3,14**
Average consumption reduction	**19%**	**40%**

Considering the emission reduction targets set by leading companies in the sector for the coming years, a 19% reduction in electrical consumption and a 40% reduction in thermal consumption are significant goals, similar to those for natural fibers. Any remaining emissions should be offset by transitioning to less polluting or renewable energy sources.

6. Conclusions

A bibliographic study, audit program, and data analysis has been carried out for the fabric exhaust dyeing process. From the data analysis phase, it is concluded that a larger sample of factories using technologies other than the most common one, Jet, would be necessary to better understand how consumption is influenced by different dyeing technologies. On a global level, a larger sample would also be needed to understand the influence of other variables, such as pre-treatment before dyeing, post-dyeing finishes, the liquor ratio, or the fabric weight.

For the audited and subsequently analyzed sample, it was possible to determine the influence of machinery age on energy consumption (both electrical and thermal), and optimal consumption values (specific electrical and thermal consumptions) were established based on the type of fiber treated for the Jet technology, which is the most widely used.

The established consumption targets are reasonably feasible according to a set of criteria, and achieving them would represent a significant reduction in the overall consumption of the analyzed factories. Other measures to further increase the reduction in emissions from these processes would involve the switch to less polluting or renewable energy sources.

Nonetheless, it is evident that the modernization of machinery, the implementation of energy efficiency measures as described throughout the document, and proper preventive maintenance of facilities are crucial.

Possible areas for improvement to complement this work include:

- A more extensive literature review to better study the root causes of variability in energy consumption across different fabric exhaust dyeing technologies.
- Increasing the audit sample size to improve conclusions obtained for the fabric exhaust dyeing process.
- Improving the measurement and monitoring systems for consumption and production by process in the factories. Accurate reflection of energy consumption and production values taken during audits is essential for the correct determination of consumption targets for each process.

Appendix A

Below are the collected data on the variables studied for the batch dyeing process of textiles, specifically: dyeing type, machinery age, energy sources, percentage of natural and synthetic fibers, and pre-treatment and post-dyeing finishing processes.

Table 16. Data gathered during the energy audits on factories performing the fabric exhaust dyeing process.

	Type of dyeing	**Age**	**Energy sources**	**% nat**	**% synt**	**Pret.**	**Finis.**
BG_018	Beck / Winch	+25	Electricity, Hot water, Vapour, Compr. Air	100	0	Yes	No
CH_003	Jets	5-15	Electricity, Vapour, Compr. Air	0	100	No	No
CH_004	Jets	0-5	Electricity, Vapour	0	100	No	Yes
CH_008	Jets & Jigger	5-15	Electricity, Vapour	0	100	No	No
CH_013	Beck / Winch	5-15	Electricity, Vapour	80	20	No	No
CH_014	Jets	5-15	Electricity, Vapour	70	30	No	No
CH_022	Jigger	5-15	Electricity, Vapour	58	42	No	No
IN_019	Jets & Jigger	15-25	Electricity, Vapour, Compr. Air	60	40	No	No
IN_026	Jets & Jigger	+25	Electricity, Vapour, Compr. Air	0	100	Yes	No
IT_005	Beck / Winch	5-15	Electricity, Vapour, Compr. Air	100	0	No	Yes
PT_008	Jets	5-15	Electricity, Vapour, Compr. Air	60	40	Yes	No
PT_009	Jets	5-15	Electricity, Vapour, Compr. Air	90	10	Yes	Yes
PT_020	Jets & Jigger	5-15	Electricity, Vapour, Compr. Air	60	40	No	No
PT_025	Jets & Jigger	15-25	Electricity, Vapour, Compr. Air	90	10	No	No
SP_003	Jets	15-25	Electricity, Vapour, Compr. Air	30	70	Yes	No
SP_006	Jets	5-15	Electricity, Vapour, Compr. Air	25	75	Yes	No
SP_012	Jets	15-25	Electricity, Hot water	5	95	Yes	No
TR_015	Jets	+25	Electricity, Vapour	10	90	Yes	No
TR_021	Jets	0-5	Electricity, Vapour, Compr. Air	35	65	No	Yes

The following tables present the characteristics of the dyeing process, including temperature, duration, liquor ratio, and fabric weight based on the type of dyeing performed:

For exhaust dyeing by jet technology:

Table 17. Data gathered during the energy audits on factories performing the fabric exhaust dyeing process. Jet technology.

	liquor ratio	Temp. nat. (ºC)	Temp. Synt. (ºC)	Dur. Nat. (h)	Dur. Synt. (h)	Grammage (g/m2)
CH_003	4		130			
CH_004	6		130			
CH_008	4		115			
CH_014	7	85	100	7,5	5	
IN_019	6	50		7,5		85
IN_026	6		135		3,5	100
PT_008	5	60	130	8	4	150
PT_009	6	80		8		550
PT_020	6	60	130	12	6	250
PT_025	5	60	100	9	5	
SP_003	10		130		5	110
SP_006	4	55	175	7	3,5	
SP_012	10		130		1	
TR_015	8	60	130	11	6	
TR_021	6	60	130	8	6	250

For exhaust dyeing by Beck/Winch technology:

Table 18. Data gathered during the energy audits on factories performing the fabric exhaust dyeing process. Beck/Winch technology.

	liquor ratio	Temp. nat. (ºC)	Temp. Synt. (ºC)	Dur. Nat. (h)	Dur. Synt. (h)	Grammage (g/m2)
BG_018	1:20	65		6		180
CH_013	1:15	110	110			
IT_005	1:20	98		3		520

For exhaust dyeing by Jigger technology:

Table 19. Data gathered during the energy audits on factories performing the fabric exhaust dyeing process. Jigger technology.

	liquor ratio	Temp. nat. (ºC)	Temp. Synt. (ºC)	Dur. Nat. (h)	Dur. Synt. (h)	Grammage (g/m2)
CH_008			115			
CH_022	1:6	90	90			
IN_019	1:1	50		24		85
IN_026	1:6		95	4		
PT_020	1:6	170	170	10	10	250
PT_025		100	100			

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