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https://doi.org/10.3390/app13085028

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Energy Efficiency Improvements in a Portuguese Ceramic Industry: Case Study

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Abstract: Taking into account the issues associated with climate change and reliance on external sources of energy, among others, the European Union and its commission have developed a strategy for transitioning to a climate-neutral economy by 2050. In this sense, a wide-ranging package was adopted to ensure the EU meets its climate and energy targets for the years 2020, 2030, and 2050. Hence, energy efficiency is a key principle of the European Union, as is energy saving and the development of new and renewable forms of energy. The most evident force is the European Efficiency Directive, adopted in 2012, which embraced a set of measures such as legal obligations to establish energy-saving schemes and/or alternative measures in the Member States. Concerning final energy consumption, the industrial sector is the second biggest consumer of final energy and one of the major contributors to greenhouse gas emissions. Some publications have studied the effectiveness of European policies, but they generally focus on a macro perspective. Few present case studies in specific industries, especially in intensive energy industries such as the ceramic industry. In this context, its higher consumption forces it to find solutions. From a challenge posed by the company, this paper presents a case study in the Portuguese ceramic industry. This study is motivated by the high energy consumption and associated costs. The main purposes of this study are to check the effectiveness of the applied measures resulting from the audit carried out in 2018, to improve energy efficiency, and to study the feasibility of implementing renewable energy sources. This work consisted of four phases: (i) studying the significant impacts of energy costs on the company; (ii) verifying if the energy indicator goals were achieved, using the 2018 energy audit as a reference; (iii) suggesting actions to improve energy efficiency and checking their effectiveness; and (iv) studying the feasibility of implementing renewable energy sources. The measures taken not only contributed to the achievement of the company's goals established in the Portuguese National Energy and Climate Plan but also enabled them to meet the annual and end goals for 2024 outlined in their energy rationalization plan. This was a consequence of the mandatory energy audit conducted in 2018 under the Portuguese Intensive Energy Consumption Management System (IECMS). In this sense, this case study provides a practical demonstration of how mandatory European policies and regulations at the member state level can help enterprises improve their energy efficiency. It also highlights the importance of evaluating renewable energy constraints rather than adopting them directly as a panacea.

Keywords: ceramic industry; IECMS; energy efficiency; renewable energy; retouching; case study

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Citation: Carvalheira, S.; Oliveira, M.; Robaina, M.; Matias, J.C.O. Energy Efficiency Improvements in a Portuguese Ceramic Industry: Case Study. *Appl. Sci.* **2023**, *13*, 5028. https://doi.org/10.3390/app13085028

Academic Editor: Fernanda Andreola

Received: 28 March 2023
Revised: 11 April 2023
Accepted: 12 April 2023
Published: 17 April 2023

1. Introduction

Worldwide observed and anticipated climatic changes (CC) for the twenty-first century and global warming are significant global changes. Climate change is characterized based on the comprehensive long-haul temperature and precipitation trends and other components such as pressure and humidity levels in the surrounding environment [1]. Anthropogenic activities are currently regarded as most accountable for CC [2] and include intensive agriculture, fuel-based mechanization, burning fossil fuels, and deforestation, among others. This means that CC is increasingly felt worldwide and is a major concern [3].

The core goal of the Paris Agreement is to enhance the worldwide response to the menace of climate change by ensuring that the global temperature rise this century stays well below 2 °C over pre-industrial levels and by striving to limit the temperature increase to 1.5 °C through concerted efforts [4]. This agreement aspires to strengthen nations' efforts to reduce greenhouse gas (GHG) emissions and pursue climate-resilient paths [5].

Energy consumption has mounted GHG levels concerning warming temperatures, as most of the energy production in developing countries comes from fossil fuels [3,5]. This means that the use of energy from fossil sources generates greenhouse gases, which have negative impacts on Earth. Examples of the impacts of climate change include the documentation of maximum and minimum temperatures observed in various regions of the world, the increase in average sea levels resulting in floods, the scarcity of potable water, and food insecurity [6]. Such impacts cannot be ignored, so it is imperative to resort not only to renewable energy sources but first of all to reduce energy waste. On the other hand, in the context of climate change, it is necessary to fulfill the commitments assumed at the Paris Agreement in 2015 and more recent ones, such as the Conference of the Parties (COP26) in Glasgow in 2021. This entails recognizing that energy is a vital factor in maintaining competitiveness between countries and their industries, but at the same time, it is the main source of greenhouse gas emissions.

In this sense, the European Commission has a strategic long-term vision to lead the transition towards a climate-neutral economy by 2050, in line with the objectives of the Paris Agreement. Building on the EU's international commitments, in 2009 the EU adopted a wide-ranging package where it located legislation to ensure the EU meets its climate and energy targets for the year 2020 (EU's "20-20-20" targets—20% increase in energy efficiency, 20% reduction in greenhouse gas emissions (from 1990 levels), and 20% renewables by 2020). In 2016, in the Clean Energy for all Europeans package [7], the European Commission set tasks to bring EU energy legislation into line with the new 2030 climate and energy targets, stressing "Energy efficiency first" as one of the key principles of the Energy Union [8]. Hence, energy efficiency is a key principle of the European Union, and the EU has promoted energy efficiency, energy saving, and the development of new and renewable forms of energy. The most evident force is the European Efficiency Directive [9], adopted in 2012, which embraced a set of measures such as legal obligations to establish energy-saving schemes and/or alternative measures in the Member States.

The awareness of studying the impact of energy on different activities and economic sectors has gained renewed interest due to the growth and high variability of energy prices. This has been aggravated by recent world events, such as the COVID Pandemic and the war in Ukraine. The need for decreasing energy imports (dependence) as a result of the standardization of energy prices will be mandatory due to the exponential pressure for the reduction in fossil energy consumption. Accordingly, the European Union considers as a priority the increase in energy efficiency and energy production through renewable sources (Portuguese Energy and Climate Plan (PECP—PNAC in Portuguese)) [10].

The interest in these issues has developed across all economic sectors, not only because it results in reduced production costs but also because it has a positive impact on environmental sustainability by reducing externalities.

Concerning final energy consumption, the industrial sector is the second biggest consumer and a major contributor to greenhouse gas emissions. Some publications have studied the effectiveness of European policies, but they generally focus on a macro perspective [8,11]. Few [12–14] present case studies in specific industries, particularly in intensive energy ones, such as the ceramic industry. In this context, its higher consumption forces it to find solutions. The industrial sector in Portugal consumes 30% of total national energy consumption [15,16] and is one of the sectors that most seek energy efficiency. The Portuguese

Intensive Energy Consumption Management System (IECMS—SGCIE in Portuguese) is especially dedicated to industry, and it is under the operational management of ADENE (Portuguese Energy Agency). This program is operated at energy-intensive installations and realizes periodic energetic audits to analyze the use of energy in these facilities and to suggest measures to increase energy efficiency in the audited installations. In particular, the ceramic industry is highly energy-demanding, which makes this industry a key point for Portugal to achieve the objectives set out in the 2030 PNEC.

Having in mind the challenge posed by the company, the specific main aim of this study was to analyze the fulfillment of the settled goals in the Energy Consumption Rationalization Agreement (ARCE, in Portuguese) agreed upon between a Portuguese ceramic company and the ADENE. This study aimed to improve the company's energy efficiency, with a particular focus on increasing product quality, reducing retouching, and avoiding energy waste. Moreover, the feasibility of installing renewable energy production was studied, particularly solar and wind energy sources. This was conducted with the aim of considering renewable energy sources as the most affordable method to reduce energy costs and eliminate the use of fossil fuels, which have severe environmental impacts [14].

This case study provides a practical demonstration of how mandatory European policies and regulations of member states can help enterprises improve their energy efficiency. It also highlights the need to evaluate renewable energy constraints and not adopt them as a panacea. Therefore, the company's environmental sustainability can be promoted, as well as this case study can enhance other ceramic facilities to adopt similar sustainable measures. For that, Section 2 characterizes the ceramic industry and its energy needs. Section 3 presents the materials and methods, and the results are presented in Section 4. In its turn, the analysis of the implementation of energy efficiency measures from the 2018 audit is made in Section 5, and the suggested measures to reduce energy consumption and/or energy costs are presented in Section 6. Finally, the conclusions and final considerations, research limitations, and future studies and recommendations will be presented.

2. Characterization of the Ceramic Industry and Its Energy Needs

The ceramic industry can be subdivided into three subsectors: construction ceramics, utilitarian and decorative ceramics, and technical ceramics. Construction ceramics is still divided into structural ceramics and finishing ceramics [17].

According to the 2020 Portuguese energy balance, 77% of final consumption in industry is attributed to the cement, ceramics, glass, and glassware sectors [15,16]. Moreover, the energy costs of ceramic industries represent a huge part of the total production costs. The ceramic industry represents about 16% of energy consumption in Portugal, mainly in the production phases of cooking and drying [15,16].

The ceramic industry can be characterized as a sector where the diversity of products, technologies, and markets is very evident. The majority of production derives from small and medium-sized companies that are highly energy dependent, mainly on thermal energy [18].

In this sense, several types of equipment make the ceramic industry an intensive energy consumer, mainly in the drying and firing processes [19]. Concerning the drying process, it is essential to gradually remove the excess water present in the paste after the conformation stage so that the products can be cooked efficiently. The temperature at the entrance of the material is lower since the heat requirements are not as high. In the final stage, the temperature must be higher so that heat transfer occurs with the water evaporation, thus avoiding damage to the products. There are different types of dryers used by the ceramics industry, particularly "Anjou" rapid dryers, vertical rack rapid dryers, horizontal roller dryers, tunnel dryers, and static chamber dryers [17].

The cooking process alters the physical and chemical properties of the material, giving it the specifications required for the final product. When the pieces reach this stage, they have already been dried, glazed, or decorated. To obtain the final product, this industry has many different types of ovens [17].

In 2020, the final energy source most consumed in Portugal's ceramic industry was electricity (33%), followed by natural gas (23%; see [15,16]). According to SGCIE [20], the primary energy source consumed is notoriously natural gas, with a value of 27,513 toe, which represents 71.5% of the sector's primary energy consumption (Table 1).

Table 1. Annual primary energy consumption and CO_2 emissions from IECMS installations [20].

Energy	Final Energy		Primary Energy		CO_2 Emissions	
		Unit	**[toe]**	**%**	**tCO_2**	**%**
Electric Energy	50,089	MWh	10,769	27.9	23,541	24.0
Natural Gas	25,556	t	27,513	71.5	73,836	75.3
Liquefied Petroleum Gas	28.3	t	31.8	0.1	84	0.1
Diesel	177	t	181	0.5	561	0.6
Gasoline	1.3	t	1.4	0.0	3.8	0.0
Total			38,496	100	98,025	100

3. Materials and Methods

The case study was the research method used. It is an empirical study that intends to determine or corroborate a theory. It suits operational and organizational dilemmas and allows the implementation of improvements to combat verified problems (Brown et al., 2018). In this type of method, the central questions are "how" and "why," and the researcher cannot control events. According to Yin [21], the case study belongs to the typology that qualitative research uses. The context addressed in qualitative research is a real context. The data collection takes place directly at the research site, and descriptive data collection techniques are used [21].

To this end, the research design adopted for this article was focused on the PDCA cycle (Plan, Do, Check, and Act). In the initial phase of this study, it was necessary to gain an understanding of the factory's background and production process, from conformation to the selection section. This was achieved through direct observation and interaction with employees from different sections of the factory. It was also necessary to understand how the equipments work, specifically the ones more energy intensive.

In the second phase, the focus was on the research objectives. Brainstorming sessions were conducted with employees at different hierarchical levels (from shop floor workers to the factory director) to explore solutions for improving equipment, methods, and processes. In these sessions, the importance of suggesting energy efficiency measures and monitoring the measures already implemented was perceived to not only anticipate their impact but also the impact of those already implemented. It is important to note that, bearing in mind the disorganization of the records of energy consumption, it was necessary to process and digitize them. Then, the follow-up on the measures implemented and the suggestions of others was conducted. To carry out the energy characterization of the equipment, a thermal analysis was performed, in particular on the different furnaces, using a thermographic camera. The data provided by the company was also analyzed to determine its energy needs. In turn, using the RETScreen® software, the feasibility of implementing renewable energy sources such as photovoltaic panels and wind turbines was studied. The implementation of energy management systems was also suggested.

At a later stage, the number of parts retouched was evaluated. Through these data, the energy gains represented by the reduction in the amounts of retouching were estimated, and the impact of this reduction on energy indicators was also analyzed. Quality control was carried out to reduce the percentage of retouched parts. On the other hand, the auditor was also accompanied in the data collection to conclude the measures implemented before this study and their effectiveness. In that analysis, some useful tools were used, standing out:

- The Pareto chart: to display quality problems and present improvement projects that arise according to their importance [22].
- The Ishikawa diagram is a schematic diagram intended to represent and simplify complex problems through the identification and grouping of their different causes [23].
- The GUT matrix is a quality tool that supports and helps in decision-making. The acronym GUT stands for gravity, urgency, and trend. The severity level is associated with the relevance of the problem when compared to the others under analysis. The level of urgency, on the other hand, denotes the importance of its resolution in a timely manner. Finally, the trend means the direction that the problem tends to take over time, that is, whether it tends to worsen or not if it is not resolved [24].

Finally, surveys were made to verify the gains that the proposed measures represent for the company, which allowed for drawing conclusions and identifying other possible improvements for future work.

4. Results

4.1. Retouching Percentage

The retouching of pieces must be minimized, as it is impossible to eliminate it since it requires a new firing and requires time, which leads to a waste of resources (material, labor, energy, among other indirect ones). As can be seen in Figure 1, there is normally an increase in energy consumption when there is an increase in the number of retouched parts. This is not possible to see in all studied months because some variables can influence it, as can the lack of all data in systems (see the explanation in the next paragraphs). However, this reveals the importance of reducing retouching and the positive impact that this decrease represents on energy consumption.

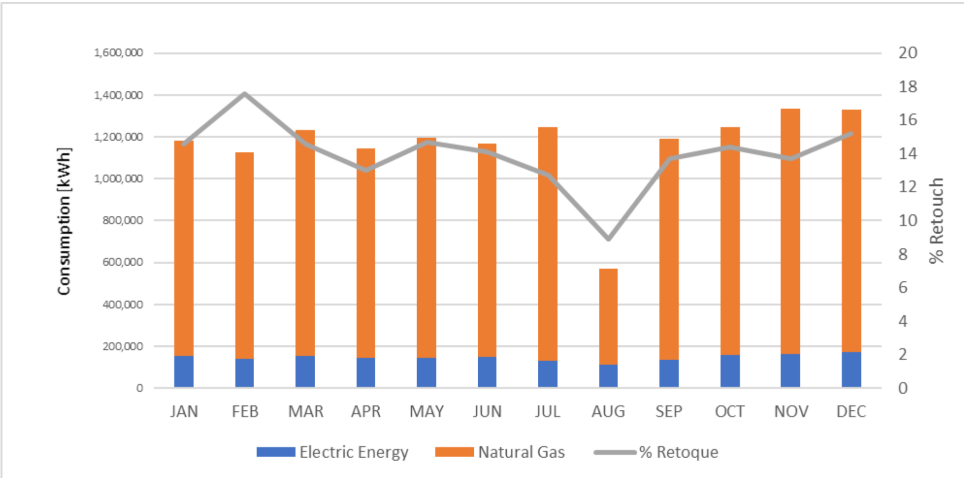

Figure 1. Energy consumption and % in retouch in 2021.

From the beginning of 2021 until the end of November, this unit had 14.21% of retouched parts, which is higher than the defined objective of 12%. Thus, it became important to analyze the most frequent defects during this period to understand their causes. To this end, the available data over this period was used to characterize the initial state.

Many of the defects detected in the retouched parts were not registered in the system, as this should be accomplished by the employees of the selection/retouching section. Therefore, the analysis was based on the records made by the employees of the selection section. The registry is made for the defect found by part reference. For example, they may check for three edge cracking defects but only record them once for that reference.

The pore defect was largely the most persistent, with a value of 63.37% of parts retouched. It is much harder to act on this defect because it may occur due to several factors.

One of them is because it is very dependent on suppliers, whose numbers are limited and some of them are unable to meet the company's needs in terms of the specifications for the pulp used. Another factor that can influence the existence of pores is single cooking (two layers are cooked in a single cooking). This type of cooking practiced in the company can generate more pores because sometimes the gas cannot escape between those layers. The company conducted various tests using pastes with different granulations to determine whether pore defects occurred less frequently based on the granulations of the pastes. This has not been the case, so tests will continue to find a viable solution. The defect known as small faults of glass/single glass had 12,14%. This percentage may seem lower, but it is still significant. In such an event, it is possible to decipher what may have occurred. This defect is often due to poor handling of the pieces right after the glazing process, which can occur in two situations: (1) when the pieces are placed on trolleys in the furnace park, and (2) when the pieces are placed in the wagons. Hence, this kind of defect is important. Figure 2 presents an example of a glaze defect, and Figure 3 shows the potential causes for the single glaze defect using the Ishikawa diagram.

Figure 2. Example of defect in small absences in glazed or glazed chipped.

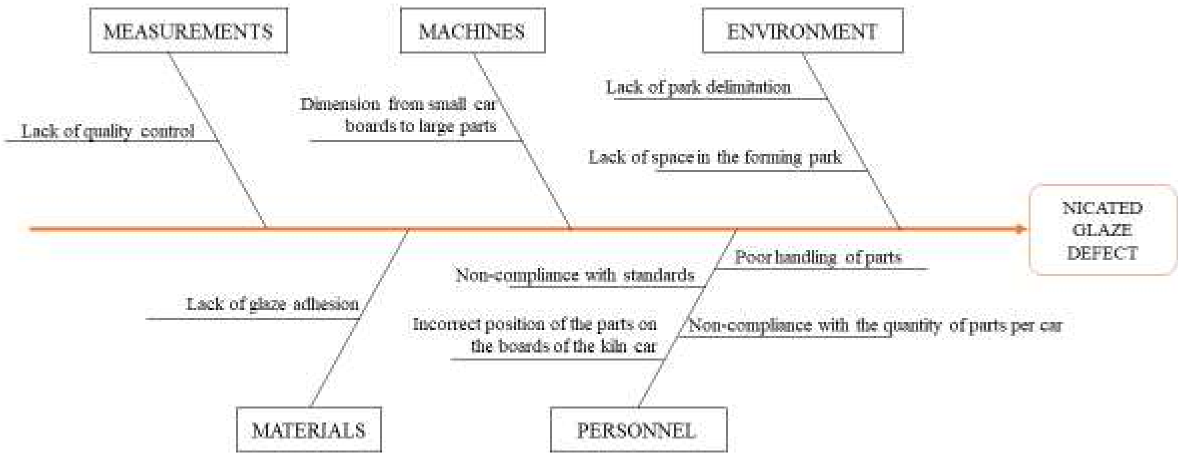

Figure 3. Ishikawa diagram of the chipped glaze defect.

Still, another defect worth mentioning is the lack of glass/color, which was 8.26%. Such non-conformity occurs due to poor tuning of the glazing machines or anomalies of the machines themselves, which do not allow the piece to be glazed uniformly.

4.2. Prioritization of the Improvement Actions

The GUT matrix was used to prioritize different tasks based on well-defined criteria in a coherent ordering of actions. In this way, the respective actions to be implemented were prioritized based on the parameters of the severity of the problem, the urgency to find a solution, and the tendency to get worse if no action is taken on it. The identified causes are related to the single glaze defect, which was the second biggest defect verified after the pore defect. The importance and priority of the improvement actions were defined through the most alarming ones from the Ishikawa diagram (see Figure 3). Five main problems stood out (detailed in Table 2). Moreover, the final scores of the causes found based on their level of severity, urgency, and trend can be seen. Numbers from one to five were assigned, with five representing greater intensity and one representing less intensity (see Table 3).

Table 2. GUT matrix for identified problems.

Problem	G (Gravity)	U (Urgency)	T (Trend)	G × U × T	Classification
Lack of quality control	5	5	4	100	1st
Incorrect disposition of cars in the park	5	4	4	80	2nd
Lack of air pressure in the wagons cleaning machine	3	3	two	18	4th
Outdated technique files	two	two	two	8	5th
Non-compliance with the furnace/de-furnace standards	5	4	3	60	3rd

Table 3. GUT matrix model [24].

Gravity	Urgency	Trend
1 = Minimal damage	1 = Very long run	1 = Disappears
2 = Light damage	2 = Long Run	2 = Slightly reduces
3 = Normal damage	3 = Middle run	3 = Remains
4 = Great damage	4 = Short run	4 = Increases
5 = Very serious damage	5 = Immediately	5 = It gets much worse

According to the analysis, it was noticed that the causes of a higher GxUxT are caused by the labor force. The lack of quality control was found to be directly associated with the absence of control over various employees in different jobs. These employees were more attentive to their tasks when they felt that their work was being evaluated. The incorrect arrangement of the cars in the park, coupled with the lack of space, resulted in an appeal to the pride of the people responsible for transporting the cars between the different points of the production process. Thus, the high percentage of defects requiring retouching was mostly due to incorrect handling of parts.

Based on the GUT matrix in Table 2, a prioritized action matrix was created and is represented in Table 4. The actions are ordered based on the final scores obtained from the problems analysis.

Table 4. Actions implemented through the final classification of highlighted problems.

Prioritization of Actions	Solution
1st	quality inspections
2nd	park delimitation
3rd	baker's evaluation
4th	equipment exchange
5th	development of software for digitizing technical data sheets

4.3. Company's Objective and Main Actions

As mentioned, the objective set by the company for 2021 was to reduce retouched parts to 12%, but this was not verified. In October 2021, there was a 14.4% retouching, and in November, the value dropped slightly to 13.7%. In this way, the company's objective is to reduce retouching to 12% by 2022. Table 5 describes the causes/problems, and solutions found. Moreover, the responsibilities of the employed actions are also assessed.

Table 5. Problems and solutions.

Problems/Causes	Solution
Lack of quality control	Retake Quality Control + Gemba Walk + Standards Control
Incorrect disposition of cars in the park	Delimit the Park (Visual Management)
Outdated technique sheets	Mapping the process (resulted in the digitization of the technical sheets)
Lack of air pressure in the wagons cleaning machine	New equipment proposal
Non-compliance with the forming standards	Visual Management

The causes/problems detected are addressed, and the solutions found to overcome them are explained in the next few points.

- Lack of quality control

To address the lack of quality control, it was necessary to conduct detailed and frequent quality inspections to detect defects early before firing. Such inspections are the most effective form of assessment. They are also crucial for planning which parts need to be fired in larger quantities to ensure orders are filled on time.

Quality inspections were carried out at different stages of the production process: after glazing, in the kiln (wagons), and when leaving the kiln. The objective was to find the possible causes of the defects and act on them. The sooner they are detected, the easier it is to fix them. The records of the inspections were carried out in Google Forms related to each of the stages of the inspections.

The results obtained throughout each week were treated and presented every Friday at the quality meetings. At the end of each month, a presentation was made with all the data for that month to verify performance and see where action could be taken to obtain better results, whenever possible. The meetings were also used to discuss the performance of different employees along the production line and assign responsibilities to those who caused the most frequent defects.

- Incorrect disposition of cars at the park

To respond to the incorrect arrangement of cars in the park, it was proposed to demarcate it with bright yellow lines that would allow for better organization. Such a measure would guide the different employees to the correct positioning of the cars in the park. As can be seen in Figure 4, the existing spaces are not enough to place more cars. The lack of space between cars leads to collisions between them and between parts. Such a collision leads to the creation of defects, in particular broken parts and parts with nicked glaze.

- Non-compliance with the oven/defrost standards

The company's failure to comply with the established oven in/out standards resulted in the creation of several defects. The workers understood the importance of complying with these standards, and images of the causes of the most alarming defects found were placed. Figure 5 shows an example of a dirty plate that led to the freight being glued to the plate, which was damaged.

Figure 4. Space between cars.

Figure 5. Dirty plate.

In addition, the ovens on each shift were assessed for compliance with the standards. If they were not following them, they were assigned a NOK, which means that they were not complying, and the reason for which they took a NOK was indicated. NOK was associated with the red color and OK with the green color. The latter represented compliance with the standards.

The implementation of such a mechanism allowed the suppliers to collaborate with the company to ensure compliance with the standards as much as possible. This action made it possible to reduce the defects caused by poor handling or other defects for which he was responsible, namely the nicated glaze.

- Files outdated techniques

The glazing technical sheets were out of date. This was due to the existence of a large number of sheets recording the glazing conditions that were filled in manually by those responsible for these sections. The record sheets were filled out per shift and each sheet had more than one reference recorded.

Digitizing this information was essential for updating the data on the glazing technical sheets. However, too much time was spent daily entering this data into the system. To solve this problem and increase efficiency, software was developed to allow direct input of glazing conditions into the system.

- Lack of air pressure in the cleaning machine

To respond to the lack of air pressure in the cleaning machine, it was suggested the development of a more suitable one that would allow more effective cleaning of the plates. The new equipment has a greater range than the old one, greater airflow, and is capable of simultaneously scraping the kiln wagon plates.

4.4. Analysis of the Savings That the Reduction in Retouching Represents

The number of pieces retouched per year is 1,749,918 on average. A reduction of 1 percentage point in retouching corresponds to 1749.92 fewer parts to be retouched per year, that is, less than 1028.95 kg (the average weight of a part is 0.588 kg). In this sense, another 1749.92 good raw pieces can go into the kiln, which increases the company's gross added value (GVA). Such an increase will lead to a decrease in the energy intensity indicator, and the specific consumption indicator would also be influenced by such a decrease since consumption decreases. Pieces that require retouching typically have different temperature curves compared to raw pieces, as they do not need to be baked at such high temperatures. Intermittent ovens are widely used for decal firing, but also for touch-up firing. However, whenever possible, it is best to bake the retouching pieces in the continuous oven. This oven consumes much less energy when compared to intermittent ones.

The consumption associated with firing retouched pieces can be determined by the percentages of retouching that are fired in each of the kilns. Thus, for instance, it is possible to estimate the savings to be obtained by reducing one percentage point of retouching. In one month, the estimated savings for a one percentage point reduction in retouching are 22,498 m^3, which represents a saving of €7987 (NG price = €0.355/m^3). The data broken down by the different ovens can be consulted in Table 6. Estimated savings in terms of natural gas consumption are also included.

Table 6. Annual savings from a one percentage point reduction in retouching.

	Oven Continuous	**Nº 5**	**Nº 6**	**Nº 7**	**Total**
m^3/kg	**0.2525**	**0.4164**	**0.3997**	**0.3610**	
kg baked retouch	20,744	4823	18,935	21,286	65,788
Savings (m^3)	5237	2008	7568	7684	22,498
Savings/month (€)	1859	712	2687	2728	7987
Savings/year (€)	22,310	8554	32,240	32,734	95,841

4.5. Impact on Energy Indicators

The purpose of quality inspections, as well as of the different measures implemented in this context, was to reduce retouching. The best measure of energy efficiency is the reduction in retouching, as this allows the firing of pieces that are more likely to be sold at their maximum value with their highest quality (pieces classified as premium pieces).

Some situations happened during the project that made the percentage of parts retouched fluctuate. On the one hand, the consequences of the pandemic situation affected some of these results, largely due to the lack of employees in the different sections as well as the lack of quality control during the January period. Another justification is the different needs of customers. The more they need parts without any defect, the more parts will be classified as "touch-up," which denotes annealing.

Table 7 compares the energy indicators before and after this case study. It was noticed that quality control is essential for obtaining parts of assured quality, which positively impacts energy consumption. Specifically, there is a slight decrease in specific consumption and energy intensity indicators, while the carbon intensity indicator remains unchanged (Portuguese Law: Government Dispatch 17313/2008).

Figure 6 shows the actual NG consumption and the comparison with the retouching percentage over this study. Records were made of the values that the NG company's counters registered. March presents the highest consumption with 85,450 m^3, and retouching was also the second highest recorded at 14.03%. In March, there was a very significant increase in this percentage due to the demand of a particular customer.

It is possible to infer that the more retouching there is, the greater the recorded consumption. This highlights the importance of reducing retouching and emphasizes the significance of quality control and the implemented actions to achieve the results outlined by the company. Despite several fluctuations throughout this study concerning the percentage of parts retouched, in April 2022 the company's objective was met since it presented 11.39% of parts classified as retouching. For this reason, the measures implemented and the quality inspections carried out ended up having a preponderant role in meeting the outlined objective of 12% retouching.

Table 7. Comparison of energy indicators at the beginning and end of this study.

Energy Indicators	Initial (January–November 2021)	Final (December 2021–April 2022)
SEC (kgoe/t)	495	489
EI (kgoe/t)	0.1007	0.0918
CI (tCO 2 e/toe)	2.531	2.531
Parts retouched	543,344	275,166

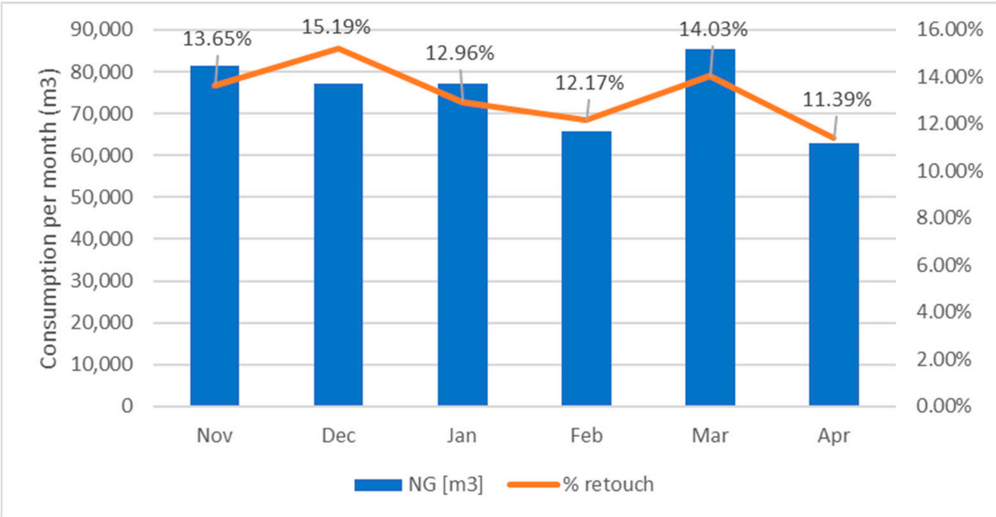

Figure 6. NG consumption and the comparison with the retouching percentage.

5. Analysis of the Implementation of Energy Efficiency Measures from the 2018 Audit

The company implemented some energy efficiency measures to comply with the Energy Rationalization Plan (in Portuguese PREn) of the audit carried out in 2018. To better understand the impact of the implemented measures, this section presents the monitoring of these measures before and after their implementation.

5.1. Replacing the Refractory Furniture in the Wagons with Low Thermal Mass Refractory Furniture from the Tunnel Kiln

The replacement of the refractory furniture in the continuous kiln wagons with low thermal mass refractory furniture was carried out during the two weeks that the continuous kiln was under maintenance in August 2021, before the start of this study. The refractory furniture with low thermal mass acquired were silicon carbide (SiC) trivets and thinner cordierite plates.

In the continuous furnace, 75 wagons pass per day, of which 25 wagons have rails and 50 wagons do not have rails. In the phase before the implementation of this measure, the wagons were composed of 16 mm thick cordierite plates, silicon carbide bars, old cordierite 80 mm props, and support plus base cordierite props, with 25 of the 75 wagons passing through the continuous kiln per day showing cordierite trivets. After the replacement, the wagons were composed of 13 mm cordierite plates, silicon carbide bars, 80 mm cordierite props, support cordierite props plus base, and 25 out of the 75 wagons that pass through the continuous kiln per day are now equipped with silicon carbide and pins. Information regarding the constitution of old wagons is presented in Table 8. The constitution of current wagons is detailed in Table 9.

Table 8. Constitution of old wagons and their respective weights.

		Old Wagons (without Rails)	Old Wagons (with Rails)
Material	**Weight per Unit (kg)**	**Number**	**Number**
Cordierite plates (16 mm)	9.40	32	26
SiC bars 40 × 30 × 1200 mm	2.51	20	20
Old cordierite 80 mm props	0.71	30	30
Support plus base cordierite props	5.99	10	10
Cordierite trivets	1.29	0	18
	Total Weight	432.27 kg	398.99 kg

Table 9. Constitution of current wagons and their respective weights.

		New Wagons (without Rails)	New Wagons (with Rails)
Material	**Weight per Unit (kg)**	**Number**	**Number**
Cordierite plates (13 mm)	7.82	32	26
SiC bars 40 × 30 × 1200 mm	2.51	20	20
Old cordierite 80 mm props	0.50	30	10
Support plus base cordierite props	5.99	10	10
Trivets SiC + pins (Imerys)	1.19	0	6
	Total Weight	375.22 kg	341.91 kg

The refractory material was weighed, and during November 2021 and January 2022, several kilns were monitored to estimate the weight of material (pieces) that each wagon can support. The natural gas consumption of these kilns was recorded to estimate the amount of natural gas needed to cook a given load of material (m^3/kg). Through these measurements, the average weight obtained per wagon was 80.61 kg, and the consumption of natural gas was 60.38 m^3/hour. An average of 3468 wagons pass during the period of 1 h and on average each wagon consumes 17.41 m^3 per firing (at 28 °C and 0.3 bar).

The financial investment for the implementation of this measure is detailed in Table 10, where the sum of the partial prices was multiplied by 60 since all 60 wagons in the continuous kiln were changed.

Table 10. Investments were made in replacing refractory furniture.

Material	Price per Unit (€)	Number	Partial Costs (€)
Cordierite plates (13 mm)	14.5	32	464
Trivets SiC + pins (Imerys)	19.75	48	474
		Total Investment	56,280

Initially, an annual gain in energy costs of €30,755 and an investment of €74,280 were foreseen, which represented an amortization over 2.42 years. What really happened was an annual gain of €24,348 on an investment of €56,280. The actual payback was 2.31, slightly lower than expected. The implementation of the measure to replace the refractory furniture in the wagons with low thermal mass refractory furniture from the tunnel kiln can be deemed successful.

5.2. Replacement of the Thermal Insulation of the Continuous Furnace in the Firing Zone

In the 2018 energy audit, a thermographic analysis revealed relatively high temperatures in the firing zone of the continuous kiln. This fact raised the alarm about the need to act on these temperatures. Figures 7 and 8 show the thermographic images obtained in the energy audit carried out by the company in 2018.

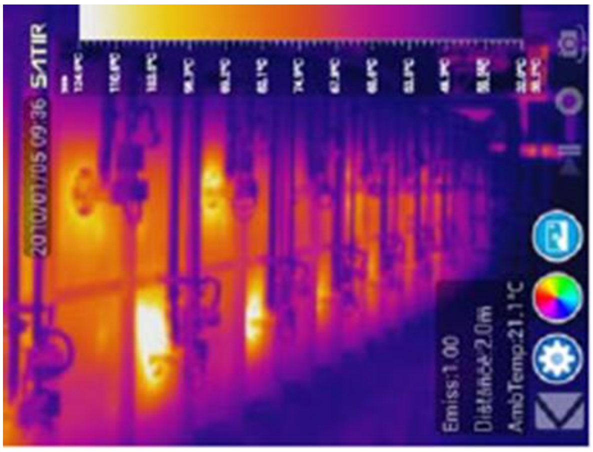

Figure 7. Firing zone of the continuous kiln of unit two before any improvement (source: Energy Audit Report 2018.

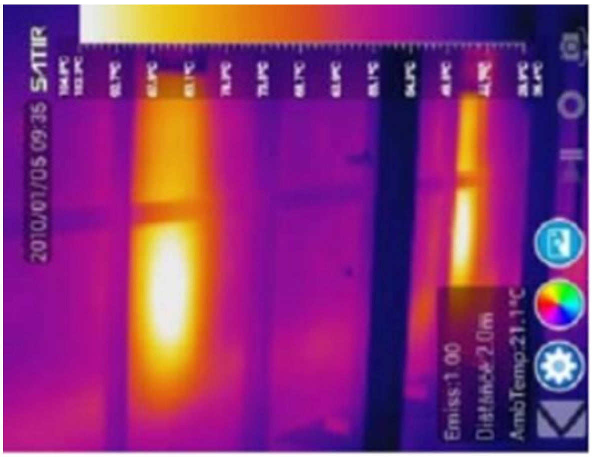

Figure 8. Cooling zone of the continuous kiln of unit two before any improvement (source: Energy Audit Report 2018).

In 2018, auditors detected radiation and convection losses and determined the total heat lost through the furnace walls to be 228,298 kJ/h. To mitigate these heat losses, thermal insulation was replaced. With this replacement, the auditors predicted that average wall temperatures would decrease from 105 °C to 80 °C and the heat lost through the walls would reduce to 140,440 kJ/h. The total amount of heat lost through the ceiling was calculated to be 120,609 kJ/h. The roof temperature was expected to decrease from 105 °C to 80 °C, resulting in a reduction in heat loss through the roof to 74,264 kJ/h. Based on the wall and ceiling audit, the total estimated energy savings would amount to 134,203 kJ/h.

The continuous oven operates 24 h per day and 335 days per year. The expected savings was 1079 GJ/year, which represents a saving of €7748.28/year for a unit cost per m^3 of €0.2763/m^3. For an estimated annual investment in thermal insulation of €45,220, the simple payback period would be 5.84 years. The replacement of the thermal insulation of the continuous furnace at manufacturing unit two was carried out in the firing zone in 2018 and consisted of replacing the fiber insulation with brick.

A thermographic analysis was performed to assess whether the intended effect of the measure was achieved, using a FLIR A320 Tempscreen fixed thermographic camera (see Figure 9). The temperatures of the walls and ceiling of the continuous furnace were compared before and after the implementation of thermal insulation in the continuous furnace.

Figure 9. Thermographic camera fixed FLIR A320 Tempscreen.

The continuous oven has an initial zone—the pre-oven—where preheating takes place with heat recovery from the oven itself from the cooling zone through fans. This zone was not considered since the temperatures of the walls are at room temperature. After this pre-heating zone, there is a door that opens to allow the wagons to pass into the kiln pre-heating zone.

The kiln walls were divided into four distinct zones for each side (left and right): a firing zone with a lower height, a cooling zone wall, a firing zone wall, and preheating zone. A total of 216 sections were created in the four zones, with a length of 0.66 each. The characteristics of the wall sections for the calculation of thermal losses are shown in Table 11.

Table 11. Characteristics of the sections for the calculation of thermal losses.

Zone	Height of Section (m)
Firing zone with lower height	1.52
Cooling zone wall	1.52
Firing zone wall	1.71
Preheating zone	1.52

The temperatures of the different sections were obtained through thermographic images captured by the Fixed FLIR A320 Tempscreen thermographic camera. The heat lost by natural convection and radiation on the walls of the continuous oven was calculated using Equations (1)–(3), which refer to heat losses from hot surfaces. The kiln's annual working time of 335 days and 24 h/day were considered. An ambient temperature of 28 °C (301 K) and a surface emissivity (ε) of 0.9 were adopted for the painted sheet. It was assumed that the geometry factor for the vertical planes was 5.22 and the geometry factor for the horizontal planes was 6.12. These values are the same as those adopted by the auditor when carrying out the 2018 audit. Equations (1)–(4) are in line with those assumed by the auditor and in accordance with the energy audit manual in the industry [25]. The thermal input, Q (kJ/h), is given by Equation (1):

$$Q = U \times A \quad (1)$$

where U (kJ/h · m^2) is the heat transfer coefficient and A is the heat transfer area (m^2). In its turn, the heat transfer coefficient is given by Equation (2):

$$U = U_r + U_c \quad (2)$$

where U_r (kJ/h · m^2) is the radiation heat transfer coefficient and U_c (kJ/h · m^2) is the convective heat transfer coefficient in the turbulent regime (tube structure). U_r and U_c are given by Equations (3) and (4), respectively:

$$U_r = 20.4 \times \varepsilon \times [((T_0 + 273)/100)^4 - ((T_r + 273)/100)]^4 \quad (3)$$

$$U_c = B \times [(T_0 - T_a)^{1.25}] \quad (4)$$

where ε is the surface emissivity, B is the geometry factor, and T_0 is the temperature of the emitting surface (°C). Additionally, Tr is the temperature of the receiving surface (°C), and Ta is the ambient temperature (°C).

The specific temperatures corresponding to each of the sections were detailed. There was great variability in temperature in each section since there was great variability in the load inside the kiln. Table 12 presents data on average temperatures in each kiln zone on both sides. Due to the difficult access to the left side of the continuous furnace, the same temperatures as the walls on the right side were considered. The average temperature of the walls was 70 °C. In this way, more significant reductions were obtained than estimated by the auditor, since he had estimated a reduction from 105 °C to 80 °C.

Table 12. Average temperatures obtained by the zone of the kiln walls on the right and left sides.

T (°C)	Firing Zone with Lower Height	Cooling Zone Wall	Firing Zone Wall	Preheating Zone
Right	69	75	71	58
Left	83	75	69	58

Regarding the oven ceiling, and due to its difficult access, the temperatures obtained were less accurate, but an attempt was made to approximate reality as much as possible. These temperatures were obtained using a thermographic camera. The presence of pipes in some areas of the ceiling of the continuous oven did not allow the temperatures to be removed from this area. Only the burning zone was considered. Table 13 shows the measurements taken.

Table 13. Measurements were carried out on the ceiling of the continuous furnace.

Ceiling	
width (m)	2.12
Length (m)	30
Temperature (°C)	114

The average ceiling temperature was 114 °C. In this way, the predicted reductions from 105 °C to 80 °C were not obtained. This fact may be due to the lack of rigor in the assessment of temperatures due to the difficult access to the ceiling of the continuous oven. Despite this, the level of reduction in global losses was higher than expected.

In the audit carried out in 2018, a reduction of 134,203 kJ/h was expected. Through the measurements and calculations carried out in this study, a reduction of 137,258 kJ/h was verified, which can be translated into savings of 3055 kJ/h greater than that foreseen in the previous audit. The price per m^3 considered was the price at the beginning of 2022 (0.355 €/m^3). The verified savings was €10,336.17/year. For the investment of €45,220, the simple return was 4.37 years. It can be stated that the replacement measure for the thermal insulation of the continuous furnace of factory unit two in the firing zone was successfully implemented.

5.3. Recovery of the Final Cooling Air from the Tunnel Kiln to the Air Dryer

When the kiln was shut down in August 2021, a system was installed to recover the final cooling air from the continuous kiln and send it to the air dryer. The thermodynamic system of the continuous furnace before the implementation of the measure is represented in Figure 10.

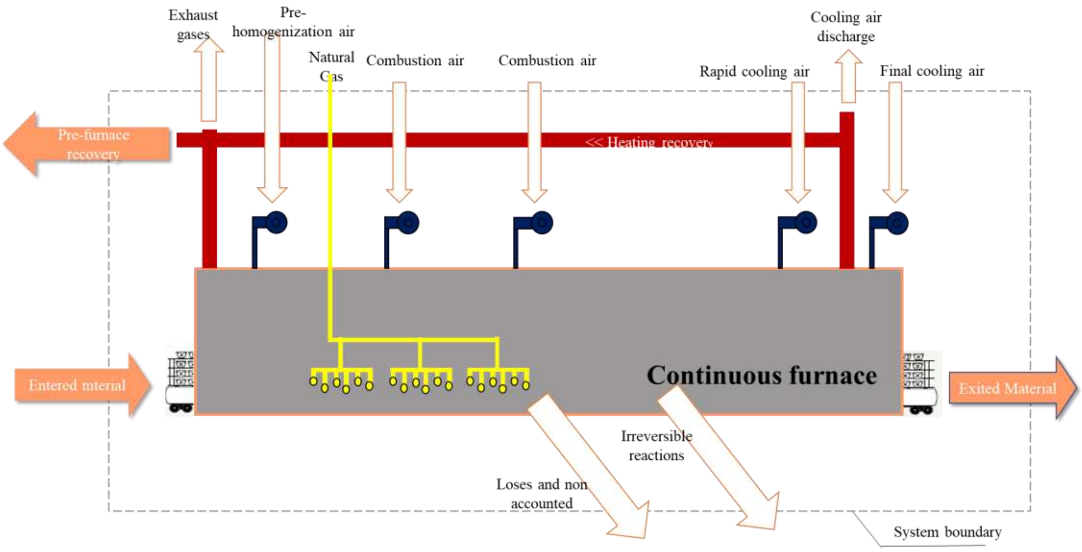

Figure 10. Thermodynamic system of the continuous furnace before the implementation of the measure.

The heat from the final cooling air that did not escape to the outside was recovered in the existing pre-furnace. The heat was not fully utilized. There was waste from the use of this heat by the chimney (Figure 10), both in the outgoing cooling air and also in the recovery for the pre-furnace. The solution was to install a valve to prevent the passage of air to the outside and install fans so that some of this heat could be used in the air dryer. The thermodynamic system after implementing this measure is represented in Figure 11. Figure 12 shows the ducts used to recover the cooling air from the continuous kiln to the air dryer.

In April 2022, the researcher accompanied the auditor to carry out some measurements. The ducts had three holes placed at strategic points that allowed obtaining the necessary values for the effective calculation of recovered heat. Using a data logger, a pitot tube, and a thermocouple, the values of velocity and temperature of the air inside the ducts were collected. To determine the volumetric flow rate of the oven's cooling air, it was necessary to measure the perimeter of the pipes. From this value, its diameter was obtained. The formula used to calculate the recovered heat, Q (kJ/h), for the air dryer and pre-furnace was shown in Equation (5) [25].

$$Q = V \times \rho \times Cp \times \Delta T \quad (5)$$

where V is the volumetric flow of the furnace cooling air (m^3/h) and ρ is the specific mass of air (kg/m^3). Moreover, ΔT is the temperature difference between the initial and final temperatures of the recovery air (°C), and Cp is the specific heat of the air (kJ/kg °C).

According to the energy audit manual used [13], the value of the specific mass of air is ρ =1.292 kg/m^3, and the specific heat of air is Cp = 1.0 kJ/kg °C. The area of the duct without insulation is 0.1942 m^2. The measurements taken are shown in Table 14.

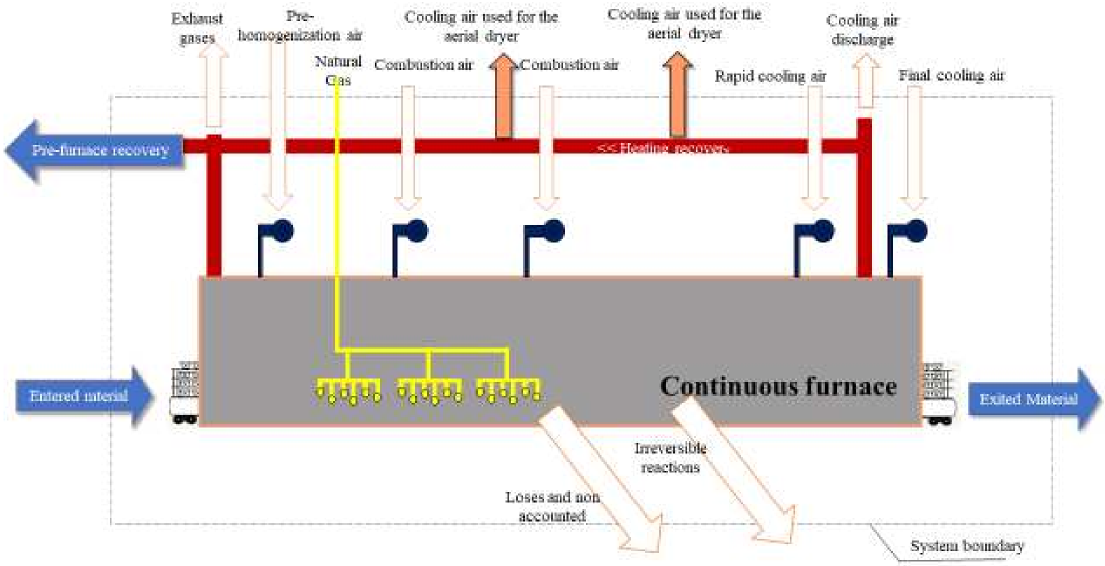

Figure 11. Thermodynamic system of the continuous furnace after the implementation of the measure.

Figure 12. Conducts in link from the oven continuous to the air dryer.

Table 14. Measurements were carried out in the holes of the continuous furnace ducts.

	Measurements Taken		
	Outwards Hole	**Aerial Dryer Hole**	**Rear Hole to the Aerial Dryer**
Average speed (m/s)	1.55	4.7	3.05
Temperature (°C)	36	384	335
Pipe diameter without isolation (m)	0.491	0.497	0.497

As the temperature measured in the orifice directed to the outside is 36 °C, and a valve was installed in the duct, can be inferred that nearly all of the cooling air is being effectively used. According to the calculations made using equation 4, the effective heat used for the air dryer was 206,781 kJ/h and 2,628,695 kJ/h for the pre-furnace.

As the heat from the cooling air is completely used for the air dryer and the pre-furnace and there is no final cooling air going outside, it can be said that the final cooling air recovery measure from the tunnel kiln to the air dryer was successfully implemented.

5.4. Impact of Energy Efficiency Measures Implemented on the Specific Consumption Indicator

After these three measures, which were implemented before and monitored during this study, it is possible to verify an important impact on energy indicators, namely on the specific energy consumption indicator of the continuous oven. In the energy audit carried out in 2018, the continuous oven had an SEC of 306.7 kgoe/t. After the implementation of the aforementioned measures, it had an SEC of 229.8 kgoe/t. This represented a reduction of 79.9 kgoe/t. Table 15 shows the comparison between the conditions before and after the measures implementation.

Table 15. Energy indicator of specific consumption before and after implementation of the measures.

Specific Consumption	Before	After	Reduction	Reduction (%)
m^3(n)/kg	0.337	0.2525	0.0845	25.1%
kgoe/t	306.7	229.8	76.9	

Thus, the reduction in a load of refractory material, the reduction in losses due to heat leakage in the furnace, and the practically total use of the heat coming from cooling for the air dryer and preheating through ducts allowed for significantly reduced specific energy consumption and consequently lower energy costs. Such energy efficiency measures had a preponderant impact on the company to achieve the objectives defined in the PNEC30.

6. Suggested Measures to Reduce Energy Consumption and/or Energy Costs

This section presents the suggested measures for reducing energy indicators and the consequent reduction in energy costs. Section 6.1 presents the design of an electricity generation system using the RETScreen® software, Section 6.2 includes energy generation systems using photovoltaic panels (see Section 6.2.1) and wind turbines (see Section 6.2.2). Finally, Section 6.3 suggests the implementation of an energy management system.

6.1. Legal and Theoretical Framework

The Portuguese Energy and Climate Plan for the 2021–2030 horizon comprises the ambitious target of reaching a 47% share of energy from renewable sources in gross final consumption in 2030. This plan promotes and disseminates the adoption of renewable energies and its objective is to make Portugal a more self-sufficient country in terms of energy production. The participation of citizens and companies in the energy transition through their investment in renewable energies was facilitated by Decree-law No. 162/2019. This decree-law established and regulated the legal regime applicable to the renewable energy production activity associated with the self-consumption of this renewable energy, namely the production of electricity through production units for self-consumption (UPAC, in Portuguese language). The UPAC are units that have renewable energy as their primary source and whose objective is to satisfy their own electricity needs. UPACs with installed power greater than 30 kW and equal to or less than 1 MW are subject to prior registration for the installation of the UPAC and an operating certificate.

The implementation of a photovoltaic system requires the dimensioning of different technologies for the system to be functional. Photovoltaic solar modules and photovoltaic inverter(s) are required. A photovoltaic solar module (commonly known as a photovoltaic panel) is the technology that allows it to capture sunlight and convert it into photovoltaic electrical energy. A photovoltaic inverter, on the other hand, allows converting the energy from direct current photovoltaic solar modules into alternating current, which makes it possible to use this energy in different electrical appliances.

To obtain the environmental analyses, an electricity emission factor of 0.257 tCO2eq./MWh was considered, which is based on the moving average of the 5 years preceding 2020 in mainland Portugal [26]. To carry out the financial analysis, an inflation rate of 5% was considered [27].

6.2. Sizing of an Electric Power Generation System Using Retscreen® Software

Retscreen® incorporates worldwide weather data. However, it does not present data relating to the city of Aveiro nor the industrial zone of Vagos, Portugal, where the case study was located. Therefore, data from the meteorological station of the University of Aveiro provided by the Meteorology and Climatology Group were used. From the available data, data on air temperature, relative humidity, daily solar radiation, atmospheric pressure, and wind speed were used. These data are necessary for the implementation studies of the photovoltaic system and the wind turbine.

It should be noted that the distance between the company and the meteorological station is around 11 km, which can distort the results from reality.

6.2.1. Power Generation System through Photovoltaic Panels

The company presents a small photovoltaic power station in its own facilities, with 408 panels. The installed power is around 108 kW. The dimensioning of this plant was designed so that during the period of less work (at the weekend), all the energy produced would be consumed within the company itself, and there would be no need to inject energy into the network. There is a lot of unused space at the moment, a space where more photovoltaic panels can be placed. In addition to the photovoltaic system, the company also has solar panels to produce domestic hot water (DHW).

Due to the global requirements regarding the adoption of renewable energies, it is important to study the feasibility of their implementation. To obtain an estimate of the amount of energy produced by this technology, the RETScreen® software was used to model it. This software is credible for estimating implementation costs, energy generation, and GHG reduction [28], and for these reasons, it was selected as the tool. A load diagram was collected, and it allows us to conclude that the factory only has appreciable consumption between 9 a.m. and 8 p.m., with a reasonably constant load profile on working days and clearly lower on weekends, when the load drops to around 100 kWh. This finding proves the goodness of the selection of the currently installed power.

However, it is assumed that the almost constant consumption during working hours on weekdays (almost rectangular profile) admits an increase in installed power to values close to 400 kW, i.e., an increase close to 300 kW.

It should be noted that a solar unit always needs a correct articulation between the number of solar modules and the characteristics of the inverter to be used, leading to a discrete number. Usually, the peak power of the modules is higher than the power of the inverter; otherwise, the inverter would be wasted. In this way, three different scenarios were considered, taking this into account.

In the first phase, a model of photovoltaic inverters was selected for this study. The considered three-phase inverter presents a maximum efficiency of 98.1%, with a maximum input power of 75 kW and a nominal output power of 50 kW. It has a maximum input voltage of 1000 Vdc (voltage direct current) with a range of 500 to 800 Vdc and a capacity of 27 kW. In addition, the necessary accessories for correct installation are included. The unit price is €4630.28. The costs for its installation are €21.8 per unit. The decennial maintenance costs (in the first 10 years) are €718.85.

Regarding the photovoltaic solar modules used, each monocrystalline silicon cell module has a maximum power of 590 W and an efficiency of 21.03%. Its voltage at maximum power is 44.77 V and its maximum current is 13.17 A. The unit cost is €228.92. The costs for its installation are €21.05 per unit. The decennial maintenance costs (in the first 10 years) are €37.50.

To carry out the sizing of each of the components mentioned above, it was necessary to understand the factory's energy needs. The contracted power is 579.61 kW. This power already considers the installed self-consumption production system, since this was implemented in 2017. Therefore, this value was the base value for carrying out the different scenarios, but always bearing in mind the factors considered (around 70%, around 55%, and around 40%), we estimated the best scenario to implement, taking into account the internal rate of return (IRR).

In the energy model of each of the conducted scenarios, the considered solar positioning system of the panels was the fixed one, and the panels' inclination was 11° (according to the company's architect) in two different orientations depending on the inclination of the roof. In this study, measurements for an inclined surface were considered. The different scenarios almost guarantee the consumption of electricity on working days, but will bring excess energy on weekends that will have to be injected into the network at market price.

The average electricity price from the network was calculated using consumption for the year 2022, for solar time, that is, peak and flood periods. The prices for each tariff period were obtained through the analysis of a February electricity bill provided by the company. The calculations performed are shown in Table 16. The average electricity cost considered for the financial analysis was €64.02/MWh. The value of the cost of the grid could be suppressed, since with solar injection there is no longer consumption, but as a precaution, it was decided to maintain it.

Table 16. Calculation of the average price of electricity from the factory network of the photovoltaic system using an invoice for the year 2022.

	Peak Load (P) (€/kWh)	Full Load (C) (€/kWh)	
Energy	0.0599	0.0588	
Grids	−0.0799	0	
Sum	−0.0200	0.0588	Total (kWh/year)
Total (kWh/period under study)	125,517	330,389	455,906
Total of each electric tariff period (€)	−2511	19,430	
Total (€)		16,918	Total Power (€)
Access to tariff power grids (kWh)	580	0.0161 (€/day)	0.0161 × 120 × 580 = 1120
Power of Peak period (kW)	423	0.2198 (€/day)	0.2198 × 120 × 423 = 11,148
Total—Electricity from grid (€)	16,918 + 1120 + 11,148 = 29,186		
Price—Electricity from grid	29,186 = 0.06402 €/ kWh = 64.02 €/ MWh 455,906		

Scenarios of 70%, 55%, and 40% of consumption

Of the contracted power of 579.61 kW and considering the inverter's rated power of 50 kW, the three scenarios of 70%, 55%, and 40% of consumption correspond, respectively, to a power to be installed of 405.73 kW, 579.61 kW, and 231.84 kW. This means the need to install 8.11, 6.38, or 4.64 inverters, respectively, in each case.

As inverters cannot be installed, it was considered: (i) 400 kW of minimum power to be installed and 9 inverters, which corresponds to 69.01% of consumption, in the 70% scenario, with 678 photovoltaic modules needed; (ii) 350 kW, which corresponds to 60.39% of consumption, in the 55% scenario, with 594 photovoltaic modules; and (iii) 231.84 kW, which corresponds to 43.13% of consumption, in the 40% scenario, with 424 photovoltaic modules needed.

The total investment costs are €211,348, €181,047, and €129,248; labor costs for the first installation are €14,468, €12,656, and € 9034, respectively, for each scenario. Regarding the environmental analysis, there would be an annual reduction in GHG emissions of 153.5 tCO_2, 134.3 tCO_2, and 95.9 tCO_2. The revenue from clean energy production is 597 MWh/year, 523 MWh/year, and 373 MWh/year and the energy generation cost is 14.15 €/MWh, 13.86 €/MWh, and 13.85 €/MWh. The IRR is 17.8%, 18.2%, and 18.2%. The payback of this project for the three scenarios would be 5.5, 5.4, and 5.4 years, which means that the project is financially viable.

IRR intends to measure the profitability of investment projects. The higher this indicator is, the more profitable the project under study. Comparing the different scenarios and their respective indicators—IRR and payback—there is a great proximity of values, with scenarios of around 55% and 40% being the best ones. Table 17 presents the indicators obtained from the three studied scenarios.

Table 17. Indicators IRR and payback from three scenarios.

Scenario	IRR	Payback
Around 70%	17.8%	5.5
Around 55%	18.2%	5.4
Around 40%	18.2%	5.4

It should be noted that electricity prices do not correspond to current values. The company has an old contract that ends in 2022, and at this time, the company will pay much more than it has paid. In this sense, the feasibility of implementing a photovoltaic system becomes extremely important to bridge the electricity bill values that tend to continue to increase in cost. Considering the liberalized market, the cost is around €215/MWh (Market Results, undated). Carrying out this study for around 55% of the contracted power, the payback would be 1.6 years.

A limitation found was that the RETScreen® software does not allow the separation of weekly consumption from consumption verified at the weekend. Energy consumption during the weekend is much lower, which would mean that a scenario with lower installed power would have a lower payback. Thus, all the energy produced, which in this case would not be consumed, would be sold at the same purchase price (64.02 €/MWh). It is important to note that if the RETScreen® software allowed the separation of weekly consumption from consumption verified at the weekend, the IRR of the lower scenarios would be higher and the payback lower, where the main difference would be the lower one.

6.2.2. Energy Generation System Based on Wind Turbines

Similar to what was presented in the previous section, an energy generation system using wind turbines is now presented. Figure 13 shows the considered wind turbine. The cost of the wind turbine was consulted on the Hummer platform (Hummer H25.0–200 kW—Livre Power, Lda, http://livre.pt/pt/185-hummer, (accessed on 15 May 2022).

Model	H25.0–200 kW
Nominal Power (W)	200,000
Maximum Power (W)	210,000
Battery bank voltage (Vdc)	480
Startup Speed (m/s)	2.5
Nominal wind speed (m/s)	11.5
Operating range (m/s)	3–25
Survival speed (m/s)	65
Generator Efficiency	>0.93
Coefficient of wind energy captured (Cp)	0.42
Generator type	Permanent magnet synchronous generator
Blade material/amount	GRP/3
Blade diameter (m)	25
Overspeed control	Follow-up mechanism + electromagnetic brake + hydraulic brake
Stopped system	Manual + automatic

Figure 13. Features of the selected wind turbine (hummer H25.0–200 kW—Livre Power, Lda, http://livre.pt/pt/185-hummer undated, (accessed on 15 May 2022).

The average price of electricity from the grid was calculated using consumption for the year 2022. The prices for each tariff period were obtained by analyzing a February electricity bill provided by the company. The calculations performed are shown in Table 18. The average electricity cost considered for the financial analysis was €60.78/MWh. In the same way as that considered for the photovoltaic system, this value will increase considerably when the company's current contract ends.

Table 18. Calculation of the average price of electricity from the wind turbine manufacturing network using an invoice for the year 2022.

	Peak Load (P)	**Full Load (F) (€/kWh)**	**Non-Peak Load (NPL) (€/kWh)**	**Super Non-Peak Load (SNPL) (€/kWh)**	
Energy	0.0599	0.0588	0.0529	0.0494	
Grids	−0.0799	0	0	0	
Sum	−0.0200	0.0588	0.0529	0.0494	Total (kWh/year)
Total (kWh/period under study)	125,517	330,389	108,573	54,250	618,729
Total of each electric tariff period (€)	−2511	19,430	5743	2678	
Total (€)	25,339				Total Power (€)
Access to tariff power grids (kWh)	580	0.0161 (€/day)			0.0161 × 120 × 580 = 1120
Power of Peak period (kW)	423	0.2198 (€/day)			0.2198 × 120 × 423 = 11,148
Total—Electricity from grid (€)	25,339 + 1120 + 11,148 = 37,607				
Price—Electricity from grid	37,607/618,729 = 0.06078 €/kWh = 60.78 €/MWh				

The factory has a contracted power of 579.61 kW. In line with the best scenario found for the photovoltaic system, the installation of a wind turbine began by dimensioning to satisfy a power of 450 kW. The considered wind turbine has a nominal power of 210 kW. Thus, to approach the dimensioning of the desired power, it is necessary to install two wind turbines.

According to the international standard IEC 61400-1:2019, the design of wind turbines is certified for a useful life of 20 years, which is the value used in this study.

The financial feasibility of implementing two wind turbines is presented in Table 19, and the project is not viable. The return on equity is greater than the lifetime of the project, and no energy production is expected.

The area where the factory is located is characteristically an area of constant winds with an annual average speed of 2.3 m/s. These characteristics make this wind turbine project unfeasible because the turbine needs winds of around 3 m/s to produce energy. This can be verified through the wind turbine power curve data shown in Figure 13. Additionally, this can be seen from the wind turbine power curve data presented in Table 20.

As previously mentioned, the low wind speeds make the installation of wind turbines unfeasible. However, according to Ma and Javed [29], there is a growing trend toward combining solar energy and wind energy to mitigate environmental concerns and meet energy needs. In this sense, there would be the possibility of installing a hybrid system—photovoltaic panels and wind turbines. This system would make up for the lack of sun exposure at night and during the winter months. However, as previously verified, wind speeds make this idea apparently not feasible. On the other hand, these studies may result in the implementation of renewable energy measures rather than energy efficiency measures. In reality, the company consumes the same amount, i.e. there is no reduction in consumption. However, the energy it needs to buy from the grid is not enough to satisfy its energy utilities. In this way, and in the Portuguese context, the national energy agency does not accept that the incorporation of a photovoltaic system for self-consumption or the implementation of wind turbines are the only measures proposed in the preparation of an energy audit.

Table 19. Financial feasibility of the project.

	Financial Feasibility	
IRR before fees-own capital	%	negative
IRR before fees-assets	%	negative
IRR after fees-own capital	%	negative
IRR after fees-assets	%	negative
Simple payback	year	
Own capital payback	year	>project
Net present value (NPL)	€	−789,912
Economic Life cycle	€/year	−39,496
Cost-Benefit Ratio		0.00
Energy generation cost	€/MWh	−335,544.32
GHG reduction cost	€/tCO2	Without reduction

6.3. Implementation of an Energy Management System

The company did not have an energy consumption monitoring system. This fact made it impossible to break down the consumption of all the machines. The simultaneity of its operation also made this disaggregation difficult. According to ISO 50001:2018, the implementation of an energy management system (EnMS) allows for the creation of conditions that improve energy efficiency, but it does not, by itself, guarantee energy efficiency. The implementation of a monitoring system does not directly result in a reduction in energy consumption. However, if well-designed, it can facilitate the identification of less efficient sources and enable the correction of these inefficiencies, leading to energy savings. Organizations can seek certification if they implement an EnMS in accordance with the ISO 50001:2018 standard and find it suitable for their needs.

However, regardless of certification, the advantages of implementing this type of system are as follows [30]:

- Preservation of natural resources;
- Decrease in environmental pollution;
- Reduction in energy costs;
- Greater energy efficiency;
- Compliance with legal requirements;
- Standing out in relation to the competition that still does not consider this cause;
- Improvement of the organization's image reveals a concern with environmental issues.

In general, and according to Gaspar [31], typical savings acquired exclusively from monitoring and controlling energy consumption can be 3% in the case of electrical consumption and 5% for other forms of energy. Now, to assess the hypothetical annual savings that the adoption of an EnMS would bring to the company, energy consumption for the year 2021 was considered, with potential savings of 3% for electricity consumption and 5% for natural gas. Thus, in 2021, the factory consumed 380 toe of electricity and 938 toe of natural gas. Such consumption would represent a total savings of €16,173 (€5522 in electricity and €10,651 in natural gas). With an initial investment of around €20,510, according to the study carried out by Bezerra [32], the estimated return can be obtained in 1.27 years. This value is within acceptable values according to the Intensive Energy Consumption Management System [20]. The IECMS states that the implementation of this measure has an average payback of 3 years, and the financial return value can vary between 1.2 years and 3.2 years.

Table 20. Power curves and wind turbine energy curve data.

Wind Speed (m/s)	Power Curve (kW)	Energy Curve (MWh)
0	0.0	
1	0.0	
2	5.0	
3	11.0	111.2
4	17.0	195.3
5	28.0	312.4
6	38.0	455.7
7	49.0	605.0
8	64.0	740.8
9	88.0	850.0
10	131.0	927.1
11	178.0	972.8
12	200.0	991.3
13	200.0	988.5
14	200.0	970.1
15	200.0	940.8
16	200.0	
17	200.0	
18	200.0	
19	200.0	
20	200.0	
21	0.0	
22	0.0	
23	0.0	
24	0.0	
25–30	0.0	

Nevertheless, the energy management system must be considered a management tool for the factory and not a control tool. The implementation of this type of system allows instantaneous energy radiographs, that is, at the moment they are taken. Furthermore, it allows for the regular collection of information with the expectation of eliminating energy waste both at the behavioral and activity levels. However, energy management systems must be supported by energy audits and different consumption reduction interventions [18].

Still, in the context of an energy management system, increasing efficiency in energy consumption depends a lot on the individual responsibility of each employee at their workstations. That is why it is extremely important to raise the awareness of all employees about the adoption of good energy efficiency practices in the daily operation of the company. The adoption of such behaviors can result in a reduction in consumption and a consequent reduction in the energy bill, eliminating unnecessary expenses.

Training in energy efficiency makes it possible to indirectly reduce energy consumption through the adoption of more efficient and sustainable practices in the company. There is still little environmental awareness among people, so alerting them to this issue is crucial. Some of the most common habits observed in the company that represent unnecessary expenses are cleaning clothes and surfaces with compressed air, leaving lights on unnecessarily, keeping air conditioning on in the winter, and not turning off computers overnight. These are all practices that are easy to avoid, and in training and awareness actions, it is essential to address the following topics:

- Energy savings benefits;
- Environmental impacts of energy use;
- Individual civic attitudes to saving energy;
- Energy dependence of the company and possible improvements in energy performance.

This section has provided suggestions for reducing energy consumption and costs. In addition to the design of renewable electricity generation systems using Retscreen® software, the implementation of an energy management system was also addressed, and the importance of training and energy awareness in the company was highlighted.

7. Conclusions

Two different factors were perceived to improve energy consumption throughout the production process: the percentage of retouching and the quality required for the final product. These two factors are crucial for the company's energy consumption and the costs it entails. Reducing the number of retouched parts required, aligning employees with the company's objectives, insisting on the correct handling of parts, and also insisting on the importance of complying with work standards.

Monitoring some of the energy efficiency measures applied by the company as a result of the last energy audit was an important step towards realizing that the measures were successfully applied. These measures had a real impact on the company's energy savings. The exchange of refractory furniture for refractory furniture with low thermal mass, the replacement of the thermal insulation of the continuous furnace, and the use of the final cooling air from the continuous furnace for the aerial dryer resulted in a decrease in the specific consumption of the continuous oven. This reduction in energy consumption represents cost savings for the company. The company's potential for the installation of renewable energies was also perceived, namely the installation of photovoltaic panels and the advantages that this would bring to the company in the long term. In addition to being able to self-produce its own energy and reduce energy costs, the company has contributed to a greener world. All of this is in line with the company's environmental concerns. It is important to highlight the importance of raising the awareness of different employees about the energy crisis that we are experiencing. It is crucial to keep people motivated and aware to walk in the same direction and think about the benefits for the company and consequently for each one individually.

Some limitations were felt with this study. The lack of training for employees in the different sections where quality inspections were carried out led to some resistance to the suggestions made within the scope of this research. These limitations influenced the result obtained from the percentage of retouching at the end of the project. In addition, the Retscreen® software does not allow a distinction between weekday and weekend energy consumption. This was an obvious limitation to the realization of this project because it evidently influenced the data obtained in the different scenarios studied.

There are some proposals for future studies. For example, a detailed analysis of the company's different equipment, but in particular the biggest energy consumers, detected some possibilities of using heat, in the case of ovens. Another suggestion would be to study the viability of using the cooling heat of three intermittent kilns in a "cascade" due to their arrangement (side by side), which implies a phased operation between them. Another proposal involves studying the possibility of incorporating green hydrogen into the factory to replace or even incorporate the natural gas energy source, which is the most harmful to the environment. In the continuous kiln, it may be possible to use the cooling air at the kiln outlet for the burners. This would allow the burners to start their functions at higher temperatures (around 225 °C) instead of ambient temperature, which would result in lower consumption. Installing consumption meters in the main equipment would be an added value to control these same energy consumptions in more detail.

The study of alternatives for the automatic control of the oxygen mixture in the continuous oven of the factory, which is currently in constant flow, would be advantageous in terms of energy consumption. Only the necessary amounts of oxygen would be used, which is essential for the correct firing of the stoneware pieces.

Concerning quality control, it is suggested to create a data entry system using a mobile device, which would allow the entry of defect data directly into the system. This would save time, allow more quality inspections to be carried out, and even increase the variety of inspected references. Last, but not least, is the use of technologies from Industry 4.0.

As a final remark, it is important to note that this case study provides a good practical example of how policies and regulations can contribute to fostering enterprise energy efficiency and the use of renewable energy as a potential solution. Therefore, it can inspire other intensive energy industries, mainly ceramic facilities, to adopt similar sustainable measures.

Author Contributions: Conceptualization, S.C. and J.C.O.M.; methodology, S.C. and J.C.O.M.; validation, J.C.O.M., M.R., and M.O.; formal analysis, S.C.; investigation, S.C.; writing—original draft preparation, S.C.; writing—review and editing, J.C.O.M. and M.R.; visualization, J.C.O.M.; supervision, J.C.O.M. and M.O.; project administration, J.C.O.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Ethical review and approval were waived for this study. The University of Aveiro institution requires an Institutional Review Board only for studies involving life science, drugs, and non-anonymous data.

Informed Consent Statement: Informed consent was obtained from all subjects involved in this study.

Data Availability Statement: Not applicable.

Acknowledgments: This work was supported by the research unit on Governance, Competitiveness and Public Policy (UIDB/04058/2020), funded by national funds through FCT—Fundação para a Ciência e a Tecnologia.

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

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