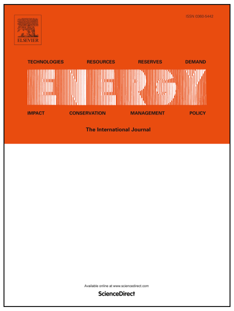

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Energy Management In The Portuguese Ceramic Industry: Analysis Of Real-World Factories

Luís Ruivo*, Michael Russo, Rúben Lourenço, Daniel Pio

Department of Environment and Planning, Centre for Environmental and Marine Studies (CESAM), University of Aveiro, Campus Universitário de Santiago, 3810-193 Aveiro, Portugal

*Corresponding author: luis.ruivo@ua.pt (L.C.M. Ruivo)

Abstract

The Portuguese ceramic industry is characterized by SME industries with high thermal energy consumption. Thus, the implementation of energy efficiency measures should include no-cost solutions, which are generally not explored in literature. This paper analyses the energy profile of different ceramic sub-sectors to identify potential improvements to meet low-cost competition in the market. Preliminary results of the statistical analysis suggest inefficient energy management, with a particular focus on natural gas consumption. The studied factories could easily improve profits and reduce energy consumption through good kiln operating practices. Optimization of kiln ceramic load (2-18%) and efficient combustion in the gas burners (1-11%) are examples of no-cost strategies that promote significant energy savings and carbon emissions reduction.

Keywords: Energy Efficiency, Kiln, Low-cost Measures, Ceramic, Firing.

Nomenclature

A	Area (m^2)	NG	Natural Gas
c_p	Specific Heat at constant p (kJ·kg^{-1}·K^{-1})	SMEs	Small and Medium-sized Enterprises
CE	Energy Specific Cost (€·$\mathrm{ton}_{\mathrm{mat,out}}{}^{-1}$)	toe	Tonne of Oil Equivalent
CI	Carbon Intensity (kgCO$_2$e· $\mathrm{ton}_{\mathrm{mat,out}}{}^{-1}$)	Subscript	
E	Energy (toe or GJ)	a	Annual
EEC	Electricity Consumption (kWh)	air	Total Air
FC	Fuel Conversion (-)	comb	Total Air Combustion
$\Delta\mathrm{H}$	Variation of Enthalpy (kJ)	c	Convection
$\mathrm{h}_{\mathrm{i,v}}$	Latent Heat of Vaporization (kJ·kg^{-1})	cool	Air Cooling
$\bar{\mathrm{h}}$	Heat-transfer Coefficient (W·m^{-2}·K^{-1})	c/w	Conveyor or Wagon
LHV	Low Heating Value (kJ·kg^{-1})	e	Equivalent
$\dot{\mathrm{m}}$	Mass Flow (kg·s^{-1})	F	Fuel
m	Mass (kg or ton)	fg	Flue Gases
P	Ceramic Production (ton)	i	Process stream i
P	Pressure (Pa)	In	Inlet
Q	Surface Loss (kJ)	j	Component j of process stream i
SEC	Specific Energy Consumption (kJ·$\mathrm{kg}_{\mathrm{mat,out}}{}^{-1}$)	mat	Ceramic Material
S_{p}	Potential Energy Saving (%)	mat,loss	Ceramic Loss Inside the Kiln
T	Temperature (K)	out	Outlet
UC	Unitary Cost of Energy (€·kWh^{-1} or €·Nm^{-3})	p	pressure
W	Water Mass Fraction (-)	R	Residual
Greek Symbol		rad	Radiation
ε	Emissivity Coefficient (-)	rec	Recovered
σ	Stefan Boltzmann Constant (kg·m^{-2}·K^{-4})	ref	Reference
α	Incremental Energy Consumption (toe·kg^{-1})	surf	Surface
Abbreviations		w	Liquid Water
EU	European Union	wv	Water Vapor
GHG	Greenhouse Gas Emissions	0	Fixed
IEA	International Energy Agency		

1. Introduction

According to the International Energy Agency, the past few decades have registered intense energy consumption, with a particular focus on oil and natural gas [1]. This strong dependence on fossil fuels is the largest source of anthropogenic emissions, which have been linked to impacts on climate [2]. In Europe, there has been a clear effort in reforming energy policies, from increasing renewable energy production to promoting energy efficiency, in order to achieve the established EU targets [3]. Government authorities have focused their attention on the industrial sector, as it currently accounts for 30% of final energy consumption [4].

The ceramic industry is included in the energy-intensive manufacturing sector, which accounts for 28 % of industrial energy consumption as of 2019 [5]. In this context, this industry has faced many challenges regarding the improvement of the energy efficiency of its processes, which are generally characterized by large amounts of waste heat (up to 80-95 %) [6–8]. The cost structures of energy-intensive ceramics producers are becoming disadvantaged due to the increase of low-cost competition in EU markets, whereby an effective energy management is essential to enhance their economic competitiveness and reduce environmental impacts without affecting ceramic quality requirements.

The Portuguese ceramic industry is mainly comprised by many small and medium-sized enterprises (SMEs), with diverse number of products and technological processes according to their subsector or final manufactured product. Ceramic production is divided into five subsectors [9]: structural ceramic, floor and coating, sanitary ware, household and special applications. Given the size of the companies that characterize the Portuguese ceramic industry, it is expected to encounter more barriers to the implementation of energy efficiency measures than in large companies, as a result of low capital availability [10,11]. Therefore, it is essential to obtain detailed information on energy consumption at all stages of the production process to support the implementation of appropriate energy efficiency measures. Additionally, these measures should prioritize solutions that have little to no implementation cost, since initial investment is the main barrier for SMEs [12].

Several studies have shown that the drying and firing stages are responsible for the highest energy consumption in ceramic processing [13–15]. These stages are critical to the energy optimization process since thermal energy is key in achieving significant energy savings [16,17]. Furthermore, the firing stage is typically carried in natural gas (NG) fuelled kilns with very low efficiencies (5 to 20 %) [8], where over 50 % of the energy input is lost in the flue gases and cooling gas exhaust stacks [18]. Thus, employing kiln technologies and operating practices with better performance can lead to significant reductions in both energy costs and CO_2 emissions [18,19].

In previous studies, waste heat recovery and kiln thermal insulation are suggested as suitable techniques to improve the energy efficiency of these kilns. Caglayan et al. [20] studied the potential of waste heat recovery from the cooling section of the kiln for preheating in gas burners. The authors concluded that 4.7% natural gas savings can be achieved for 148 ºC air that is taken from the cooling section of the kiln. Similar results was found by Soussi et al. [21], investigating the energy consumption reduction of a tunnel kiln by optimization of the recovered air mass flow from the cooling zone to the firing zone. The authors observed the existence of an optimal value of recovered air mass flow that can reduce the daily consumption of the natural gas up to 4.6%. Peris et al. [22] analyzed the application of an organic Rankine cycle (ORC) in a ceramic industry for low grade waste heat recovery from exhaust gases of a ceramic kiln. The aim was to recover the heat generated during the indirect cooling section of the kiln to produce electricity. The system was designed to recover a thermal power of 177 kW from the heat source and provide thermal oil at 165 ºC to the ORC module that achieved around 22 kW of gross electrical power. However, the production of electricity showed a lower efficiency (~12.5 %) compared to the current system which sends the hot air recovered in the indirect cooling stage to the dryers and burners. Alternatively, Delpech et al. [23] proposed the application of heat-pipe based heat exchanger for improving the energy efficiency of ceramic processes. A combined theoretical and numerical approach constructed by the authors demonstrated that the application of heat pipe based heat exchanger to the cooling stack of the ceramic kiln enables the recovery of more than 863 MWh of thermal energy that can be used for heating up the hot air stream of the pre-kiln dryer. Ferrer et al. [13] evaluated the energy efficiency of a ceramic tile roller kiln and found that about 20% of the energy input into the kiln was lost through kiln surfaces and uncontrolled heat losses. The conclusion was that the quality of kiln thermal insulation could be improved by reducing insulation thermal conductivity or increasing insulation thickness, in addition to improving the thermal sealing of kiln roller holders. The authors also suggested the implementation of heat recovery systems for the flue gases and colling gases since this waste energy could be recovered to the same kiln as oxidising air or to other plant facilities. Mezquita et al. [18] estimated energy savings up to about 17% when part of the cooling gases are recovered in the firing chamber and are not exhausted into the atmosphere.

Though the effectiveness of the proposed strategies to achieve energy savings, limitations to the implementation of some measures have been identified such as high investment costs [24]. Furthermore, there is a knowledge gap regarding no-cost energy efficiency strategies that could be implemented related to energy management practices, such as optimizing the kiln load during ceramic production. Studies regarding the ceramic industry are mostly focused on specific process improvements with the objective of thermal energy savings [20–23], numerical and theoretical analysis [19,25], or life cycle assessments [26,27]. Detailed kiln-specific operating data available for industrial ceramic factories is also limited, which highlights the need to study larger scale processes [28]. Such experimental data is critical to provide the required input for modelling approaches, as well as for model validation.

In the present study, different ceramic factories were selected as case studies, spanning representative subsectors of the Portuguese ceramic industry. The main objective is to analyse the energy profile of the ceramic industry to identify low-cost energy efficiency strategies that can be easily applied in SMEs, as there is an evident lack of information in literature regarding this kind of solutions, with recognized knowledge gaps in the optimization of kiln energy performance [13].

The methodology used includes a statistical analysis that expands upon the typical energetic analysis found in the literature. Afterwards, monitoring data from continuous operation of the factories was obtained and different performance indicators were calculated. To quantify the firing stage energy performance and the amount of waste heat generated, a thermodynamic analysis was done by applying mass balances, energy balances and experimental data analysis. The results obtained were compared with the best available technologies and alternative energy efficiency measures were evaluated that are not currently reported in literature, including both the optimization of the kiln ceramic load and combustion in gas burners. The firing techniques studied in this work are the most used in the ceramic industry, which means that this study can easily be extrapolated to any typical ceramic facility with a similar technological state.

2. Case Study – Description of Ceramic Companies

This study focused on three ceramic factories with different final products, from this point forward stated as factory A, B and C. In factory A, the production is centred around household ceramics, while factories B and C mainly output floor tiles and sanitaryware, respectively. Factory A and C have a continuous production throughout the year, while factory B is not regularly operational. Table 1 shows annual energy consumption and production, according to the data provided by the factory engineering team. The main form of energy used is electricity and natural gas, with NG representing from 68% to 82% of total energy consumption.

Table 1 – Annual energy consumption (toe) and production (ton) for A, B and C.

	Factory A			**Factory B**			**Factory C**		
	NG	**Electricity**	**Production**	**NG**	**Electricity**	**Production**	**NG**	**Electricity**	**Production**
1	125	28	316	5	3	0	119	48	447
2	114	16	563	152	42	1 175	133	65	484
3	138	23	486	0	9	0	150	61	578
4	116	28	459	2	3	0	141	67	556
5	109	27	278	137	41	981	151	66	554
6	122	29	439	0	6	0	145	67	559
7	130	32	736	0	2	0	146	66	596
8	41	10	0	0	2	0	72	40	220
9	137	32	579	145	34	1 159	151	69	563
10	139	30	304	39	24	348	151	68	532
11	140	29	586	62	10	484	149	69	553
12	93	21	257	98	41	690	100	62	371
Total	1 402	305	5 001	640	219	4 879	1 607	748	6 013

The factories use a similar production route which has four main stages [29]. The process begins with the preparation of raw materials (grinding, atomization and spray), which guarantees the optimal particulate size and moisture content to achieve a homogenous paste. Stage 2 is the forming of the paste, in which the paste goes through an automated press. After forming, the resulting products are subject to a drying process to remove excess moisture. Finally, the dried ceramic materials are subject to a single firing step under a high temperature atmosphere in a kiln to induce the desired physical and chemical properties. The configuration of the kiln, the firing time and temperatures vary depending on the manufactured product. Table *2* details the main characteristics of the kilns used in each of the studied factories.

Table 2 – General characteristics of the kilns in each studied factory.

	Factory A	**Factory B**	**Factory C**
Configuration	Tunnel	Roller hearth	Tunnel
Year of Manufacture	1 981	2 005	1 992
Ceramic Product	Household	Floor Tiles	Sanitaryware
Thermal Power (kW)	1 550	5 040	2 560
Production Capacity ($kg \cdot h^{-1}$)	1 000	3 000	1 125
Firing Temperature (K)	1 448	1 573	1 498
Electric Power (kW)	52.2	80.4	36.5
Length (m)	70	100	75
Ceramic Transport System	Wagon	Conveyor	Wagon

3. Methodology

3.1. Qualitative Analysis

As a first approach, it is possible to analyse the energy performance of the process by correlating real data on production with energy consumption [30,31]. The analysis of the univariate regression equation ($E = \alpha P + E_0$) can provide relevant insight into the process energy consumption. Variable 'E' is the estimated energy required for a certain value of production 'P', 'E_0' is the quantity of fixed energy consumption that is independent from production, and 'α' represents the incremental energy consumption per production unit. The model parameters 'α' and 'E_0' were obtained using ordinary least squares regression analysis and Statistical Package for the Social Sciences (SPSS) software. The coefficient of determination (R^2) was used to measure the regression prediction accuracy. The root mean square error (RMSE) of the model is another parameter to measure the quality of the fitting, which is a measure of the scatter in the data around the model. The statistical analysis was based on annual data from energy bills and production control, provided by the factory engineering team.

3.2. Data Collection

The energy profile of the ceramic companies was obtained with data collected during on-site visits. In order to quantify the energy consumption, continuous measurements of power consumption of all devices were made, using a set of Cauvin Arnoux PEL 103 analysers. Data was recorded continuously over a period of one month. The NG consumption was registered using the readings from the rotameter connected to the feed line of each equipment, while the supplier´s website was searched to determine the composition and LHV of the fuel. Based on this data and the energy bills provided, the annual energy consumption in each stage of the process can be calculated. The mass flow rates (air and flue gas) of the kiln were determined using a TCR Isostack Basic Tecora. The flue gas composition was determined by continuous monitoring of the main combustion products (CO, CO_2, O_2 and NO_x) using the Horiba PG 250 portable gas analyser. Moisture content was determined by gravimetric method. The fuel rate was obtained from direct measurement of the rotameter installed in the kiln. The mass flow rate of the ceramic material was determined experimentally, according to the quantity that entered and left the kiln in a given period. The stream temperatures were measured using a type K thermocouple. Regarding the kiln walls, a thermal imaging camera (Testo 875-1i) was used to determine the surface temperature. The data acquisition for the operating variables of the kiln was carried out over a period of 60 minutes. In Table *3*, the equipment used to acquire the data for the energy analyses is listed.

Table 3 – Equipment and methods used in the kiln variables monitored.

Equipment	Parameter	Method	Norm
Cauvin Arnoux PEL 103	Power & Energy	---	---
Type K Thermocouple	Temperature	Thermal conductivity	---
HORIBA PG250	CO	NDIR	EN 15058:2006
	CO_2		iT008 revD
	NO_x	Chemiluminescence	EN 14792:2005
	O_2	Paramagnetism	EN 14789:2005
Testo 875-1i	Temperature	Thermography	---
TCR Isostack Basic Tecora	Flow	Pitot Tipo S	NP ISO 10780:2000
	Pressure	Capsule Pressure Gauge	---
Gas Meter	Fuel Flow	Rotary Lobes	---
Kern 440-45	Moisture Content	Gravimetry	EN 14790:2005

3.3. Kiln Energy Analysis

Energy analysis is the main tool for analysing energy use characteristics and optimizing industrial kilns [23,32,33]. The proposed model is based on steady-state calculations of the various forms of energy associated with all the intervenient materials and encompasses the following terms: (i) the specific heat at constant pressure $(c_{p,i})$ associated with the mass flows $(\dot{m}_i)$; (ii) the phase change of components from liquid to vapor, which requires the latent heat of vaporization $(h_{I,v})$; (iii) the chemical energy expressed by the low heating value (LHV_i) and; (iv) heat loss by radiation (Q_{rad}) and convection (Q_{conv}). Thermodynamic calculations were performed using one second as reference base. Electrical energy consumption was not considered because this was thermodynamically insignificant. Figure 1 shows the general schematic view of all streams involved in the operation of the ceramic kilns studied.

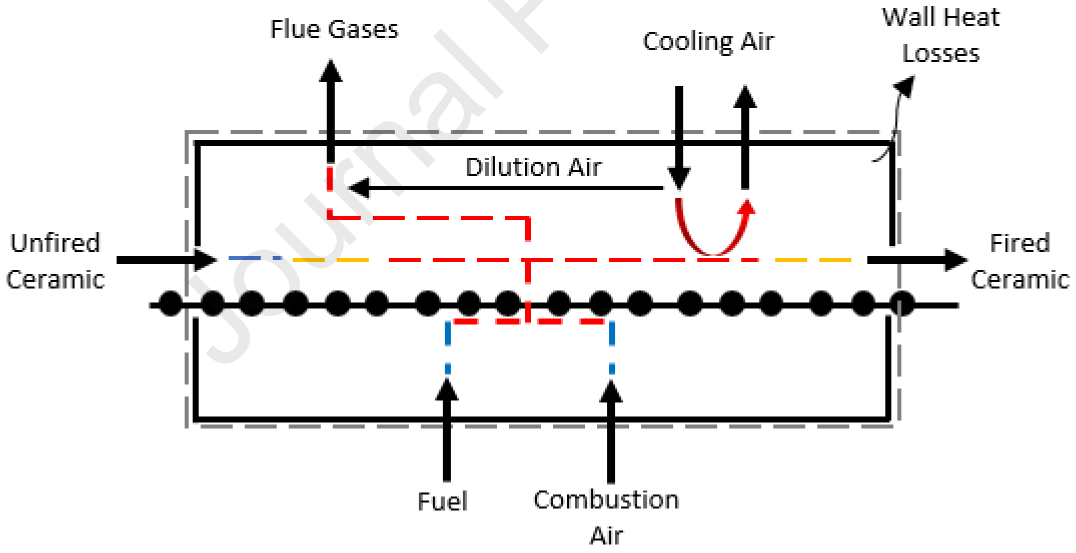

Figure 1 – General view of all streams present in the studied ceramic kilns.

Based on the previous considerations, mass and energy balance equations result from the difference between the system input and output flow streams:

$$\sum \dot{m}_{in,i} = \sum \dot{m}_{out,i} \tag{1}$$

$$\sum \Delta H_{in,i} = \sum \Delta H_{out,i} + Q_{surf} \tag{2}$$

where ΔH_{in} and ΔH_{out} are the enthalpies of the kiln input ($\dot{m}_{in}$) and output ($\dot{m}_{out}$) mass flow streams, respectively. The main energy stream at the entrance of the kiln is provided by the chemical energy of the fuel (ΔH_F). Also, the input energy flow of the ceramic material (ΔH_{mat}), conveyor belt or wagon ($\Delta H_{c/w}$) and air (ΔH_{air}) need to be considered. In the case of air, the moisture content (W_w) and the respective latent heat of vaporization (h_{wv}) are also taken into account.

$$\Delta H_{in} = \Delta H_F + \Delta H_{air} + \Delta H_{mat} + \Delta H_{c/w} \tag{3}$$

$$\Delta H_F = \dot{m}_F \cdot LHV_F + \dot{m}_F \cdot c_{p,F} \cdot (T_F - T_{ref}) \tag{4}$$

$$\Delta H_{air} = \dot{m}_{air} \cdot c_{p,air} \cdot (T_{air} - T_{ref}) + \dot{m}_{air} \cdot W_w \cdot h_{wv}(P, T_{ref}) \tag{5}$$

$$\dot{m}_{air} = \dot{m}_{comb} + \dot{m}_{cool} \tag{6}$$

$$\Delta H_{mat} = \dot{m}_{mat} \cdot (1 - W_w) \cdot c_{p,mat} \cdot (T_{mat} - T_{ref}) + \dot{m}_{mat} \cdot W_w \cdot c_{p,w} \cdot (T_{mat} - T_{ref}) \tag{7}$$

$$\Delta H_{c/w} = \dot{m}_{c/w} \cdot cc_{p,c/w} \cdot (T_{c/w} - T_{ref}) \tag{8}$$

At the exit of the kiln, the most relevant energy streams are associated with the cooling of the ceramic material (ΔH_{cool}) and the combustion gases (ΔH_{fg}). Another relevant energy fraction occurs when there is heat recovery (ΔH_{recov}), either from the exhaust gases or cooling air. It is also important to consider other energy flows of lesser magnitude associated with both the ceramic material (ΔH_{mat}) and the load conveyor belt/wagon ($\Delta H_{c/w}$) that can leave the kiln at high temperatures.

$$\Delta H_{out} = \Delta H_{fg} + \Delta H_{cool} + \Delta H_{recov} + \Delta H_{mat} + \Delta H_{conv} \tag{9}$$

$$\Delta H_{fg} = \dot{m}_{fg} \cdot c_{p,fg}\left(T_{fg} - T_{ref}\right) + \dot{m}_{fg} \cdot W_w \cdot h_{wv}(p, T) + \sum_{j=CO,CH_4}^{n} m_j \cdot LHV_j \tag{10}$$

$$\Delta H_{cool} = \dot{m}_{cool} \cdot c_{p,air} \cdot (T_{cool} - T_{air}) + \dot{m}_{cool} \cdot W_w \cdot h_{wv}(p, T) \tag{11}$$

$$\Delta H_{recov} = \dot{m}_{recov} \cdot c_{p,air} \cdot (T_{recov} - T_{ref}) + \dot{m}_{recov} \cdot W_w \cdot h_{wv}(p, T) \tag{12}$$

$$\Delta H_{mat} = \dot{m}_{mat} \cdot c_{p,mat} \cdot (T_{mat} - T_{ref}) \tag{13}$$

$$\Delta H_{c/w} = \dot{m}_{c/w} \cdot c_{p,c/w} \cdot (T_{c/w} - T_{ref}) \tag{14}$$

Additional heat losses through the walls (Q_{surf}) take place while the kiln is working. Considering as a reference the external surface of the system, the loss quantification at the kiln walls takes into account the heat transfer by radiation (Q_{rad}) and convection (Q_{conv}). The calculation of losses by radiation results from the application of the Stefan-Boltzmann law. Additionally, the losses due to convection are calculated considering a natural convection phenomenon along flat vertical surfaces [34].

$$Q_{surf} = Q_{rad} + Q_{conv} \quad (15)$$

$$Q_{rad} = A_{surf} \cdot \varepsilon \cdot \sigma \cdot (T_{surf}^4 - T_{ref}^4) \quad (16)$$

$$Q_{conv} = A_{surf} \cdot \bar{h}_c \cdot (T_{surf} - T_{ref}) \quad (17)$$

Energy calculations consider a reference environment, which has a known temperature (T_{ref} = 298 K) and pressure (P_{ref} = 101 325 Pa). In these conditions, a value of 2441.7 kJ·kg^{-1} was assumed for the latent heat of vaporization of water. The thermodynamic data, such as the specific heat, was determined through empirical formulas at their corresponding temperature [35].

3.4. Performance Indicators

The most reliable way of tracking the energy performance is the specific energy consumption (SEC), and express the ratio of measured energy (NG and electricity) with the amount of ceramic material processed over a defined period of time [28,36]. This physical-thermodynamic indicator allows to evaluate the global efficiency of the process or a particular stage/equipment and to assess the potential for energy savings (S_P), using the best available technologies as a reference (SEC_{ref}) [12].

$$SEC\ (kJ/kg_{mat,out}) = SEC_{EEC} + SEC_{NG} = (EEC \times 3600 + NG \times LHV_F)/m_{mat,out} \quad (18)$$

$$S_P\ (\%) = (SEC/SEC_{ref} - 1) \times 100 \quad (19)$$

In ceramic production, electricity and NG consumption are sources of greenhouse gas emissions (GHG). Carbon intensity (CI) associated with the production of ceramics should consider all types of energy used. The emission factor of GHG emission from GN and electricity in Portugal were 0.641 kgCO_2e·MJ^{-1} and 0.47 kgCO_2e·kWh^{-1}, respectively, according the Portuguese Energy Policy Organization [37].

$$\mathrm{CI}\ (\mathrm{kg_{CO_2e}}/\mathrm{ton_{mat,out}}) = (\mathrm{EEC}\ \times 0.47 + \Delta\mathrm{H_f}/1000 \times 0.641)/\mathrm{m_{mat,out}} \tag{20}$$

Another interesting indicator is the specific cost of energy (CE), which is an economic parameter associated with the ceramic production. This indicator can be calculated from the coefficient between the energy consumption and the amount of ceramic material manufactured. It was assumed a unitary cost (UC) of 0,372 €·Nm^{-3} for NG and 0,115 €·kWh^{-1} for electricity.

$$\mathrm{CE}\ (€/\mathrm{ton_{mat,out}}) = (\mathrm{EEC}\ \times 0.115 + \mathrm{NG} \times 0.372)/\mathrm{m_{mat,out}} \tag{21}$$

4. Results and Discussion

This section is divided into three subsections. The first shows the results of the statistical approach, analyses energy consumption for each stage of ceramic production and process performance indicators. The second discusses the results of the mass and energy balance of the studied ceramic kilns, quantifying the waste heat generated as well as the energy performance. In the last section, potential energy saving strategies with no/low-cost investment are analysed.

4.1. Energy Profile

The correlation between the energy consumption and production for the ceramic factories are shown in Figure 2. The analysis of the regression parameters is suitable only as an indicator of potential energy problems. A high correlation value does not necessarily mean high efficiency in the production process. In contrast, a low correlation value is an indication that there are inefficiencies.

Regarding NG, factory B and C show a strong correlation coefficient between energy consumption and production (R^2 = 0.994 and 0.955, respectively), suggesting a suitable control of NG. In contrast, factory A has a low correlation value (R^2 = 0.234) when compared with factory B and C. The variability of the NG consumption around the anticipated trend line is an indicator of the inefficiency of the process. Note that NG consumption tends to be lower when ceramic production increases, which is a clear indicator of weak energy management practices [38]. Additionally, energy consumption value obtained for similar production output suggest that there are periods of time where the equipment is running without any output, which negatively affects the performance of the facility. For electricity consumption, factory B stands out as having the highest correlation between consumption and production (R^2 = 0.849), while factory C (R^2 = 0.677) and factory A (R^2 = 0.333) has a moderate and low correlation value, respectively. The long-term operation of Factory A, associated with the low R^2 value obtained for the consumption of NG and electricity, suggest a poor energy management and a high level of technological obsolescence.

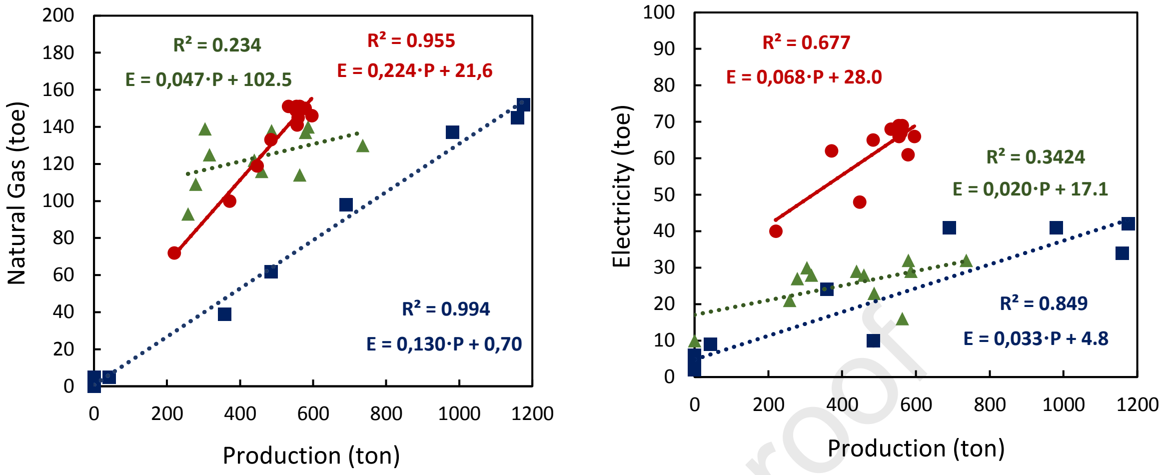

Figure 2 - Relationship between the yearly ceramic production and natural gas consumption (left) and electric energy consumption (right), for factories A (▲), B (■) and C (●).

The regression equation ($E = E_0 + \alpha \cdot P$) can provide useful information, such as the quantification of fixed (E_0) and variable energy (α) consumption. Ideally, ‘E_0’ should be zero, which would mean that the energy consumption is exclusively due to ceramic production ($E = \alpha \cdot P$). However, there are fixed energy loses resulting from the inefficiencies of the equipment, which are independent from the actual production. In the case of the equipment that requires thermal energy, heat loses occur on the outward surfaces of the equipment and the material transport system, as well as long periods without production, all of which contribute to ‘E_0’. The variable ‘α’ is the energy consumption by unit of production. Using thermal energy as an example, ‘α’ should only give the energy consumption from physical-chemical transformations of the ceramic material associated with the drying and firing stages. However, there are inevitable loses in the transport system, as well as the largest contributors to this variable, combustion gases and cooling air. For factory A, the low R^2 value does not allow us to reach any consistent conclusions regarding ‘E_0’ and ‘α‘ using the regression equation. Nonetheless, using the NG consumption information from Figure 2 (left) and electricity consumption (right), some conclusions can be drawn regarding the other two factories.

Factory B has an 'E_0' of 0.70 toe, the lowest value, which is between 0.5% and 11.4% of total NG consumption. Factory C exhibits a higher fixed energy value ('E_0') of 21.6 toe, accounting for 13.9% to 30.5% of NG consumption. These values can be an indication of inefficiencies when using equipment that requires thermal energy. Additionally, the variation in percentage of 'E_0' values suggests operation below nominal capacity, which has a negative impact in terms of energy consumption. Factory C also shows a high variable energy value ($\alpha = 0.224$ toe·ton^{-1}), in comparison to the lower value registered for factory B ($\alpha = 0.130$ toe·ton^{-1}). Although both the factories under analysis produce ceramics (household ceramic and floor tiles) that require different energy needs in the processing of the raw materials, the difference observed for 'α' suggests possible inefficiencies that may be associated with a higher level of technological obsolescence.

Similar conclusions can be drawn when analysing the electricity consumption and corresponding linear regression equations. The fixed 'E_0' value is low for factory B (E_0 = 4.8 toe), representing between 11.0% and 77.6% of total consumption. Comparatively, factory C has a much higher consumption, with E_0 = 28.0 toe, having a contribution to total electric energy consumption of 58.7 to 79.4%. This oscillating value of 'E_0' in total electricity consumption in these factories reinforces the idea that they are operating below nominal capacity. As with NG consumption, the variable energy consumption for factory B ($\alpha = 0.033$ toe·ton^{-1}) is substantially lower than factory C ($\alpha = 0.068$ toe·ton^{-1}). Table 4 shows the values for the monthly energy consumption, ceramic production and carbon intensity of each factory.

Table 4 – Monthly energy consumption (toe), production (ton), and CI ($kgCO_{2e}\cdot ton_{mat}^{-1}$).

Stages	**Factory A**		**Factory B**		**Factory C**	
	NG	Electric	NG	Electric	NG	Electric
Raw Material Preparation	-	2.5	-	3.6	-	4.4
Shaping	-	3.8	-	7.7	-	5.1
Drying	23.0	5.0	34.9	15.1	12.9	4.5
Firing	80.2	8.9	138.0	10.8	94.5	6.0
Auxiliary Equipment	-	4.3	-	7.1	6.2	37.6
Total Energy	103.2	24.5	172.9	44.3	139.4	66.6
CI	494.6	95.6	352.9	73.6	569.8	235.4
Production	560.0		1315.0		535.0	

The electricity consumption varied between 24.5 and 66.6 toe, which represents 19.2% to 32.3% of total energy consumption. The main electric consumption in factory A and B is observed for the drying and firing stages, which is justified by the use of dryers and kiln in continuous operation. However, the main electricity consumer in factory C is auxiliary equipment, compared to A and B, there is a large variation in electricity consumption of auxiliary equipment, which could justify the high 'E_0' value in the regression analysis.

As seen above, NG is the main source of energy, account for 67.7% to 80.8% of total energy consumption in the studied factories, which highlights its prevalence in the ceramic industry. The largest NG consumption was for factory B (172.9 toe), followed by C (139.4 toe) and A (103.2 toe). By analysing the energy distribution in the production stages, the highest energy consumption is in drying and firing. The consumption differs for different ceramics, but the structure mainly based on NG for firing and drying is similar for every type of final product. Firing in particular is responsible for 67.7% to 79.8% of NG consumption, requiring a more in-depth analysis to assess opportunities for increasing kiln energy performance.

Factory C shows the highest environmental impact of the three, with an emission by production unit of 805.2 $kgCO_{2e}\cdot ton_{mat}^{-1}$, followed by A (590.2 $kgCO_{2e}\cdot ton_{mat}^{-1}$) and finally B (426.5 $kgCO_{2e}\cdot ton_{mat}^{-1}$). The contribution of NG to the calculated CO_{2e} value is very high, ranging from 70.8% to 83.8% of total CO_{2e} generated during the production process.

4.2. Kiln Energy Analysis

4.2.1. Mass Balance

The information regarding the mass balance of the kilns is detailed in Table A.1. The main mass flow is from the cooling air, which represents between 83.9% and 85.5% of the total entry mass. Part of this flow is used to dilute the combustion gases on the interior of the kiln, which guarantees the desired oxidizing atmosphere for the treatment of the ceramic material [18]. The remaining air fraction is used to cool the ceramic material at the exit of the kiln. The ration between the cooling air and the ceramic material ($kg_{air,cool}\cdot kg_{mat}^{-1}$) is 36.5 for factory A, 12.4 for B and 15.9 for C. As for the exit of the kiln, the primary energy flows are from the cooling air and the combustion gases. Regarding the ceramic material, its distribution at the entrance of the system varies between 1.5% and 5.8%. There is only partial ceramic loading of the kiln in factory A (64.5%), while in factories B and C (85.3 and 91.4%) the amount of ceramic material processed through the kiln is close to the maximum production capacity. The contribution of the ceramic transport system varies between 2.3% and 6.8%. The variation in total mass between the entrance and exit of the kiln is justified by air infiltrations that occur at the kiln inlet as well as orifices and fissures in pipelines. Figure 3 shows a Sankey diagram with the distribution of the mass flow inputs and outputs for Factory A (diagrams for B and C can be viewed in Appendix B).

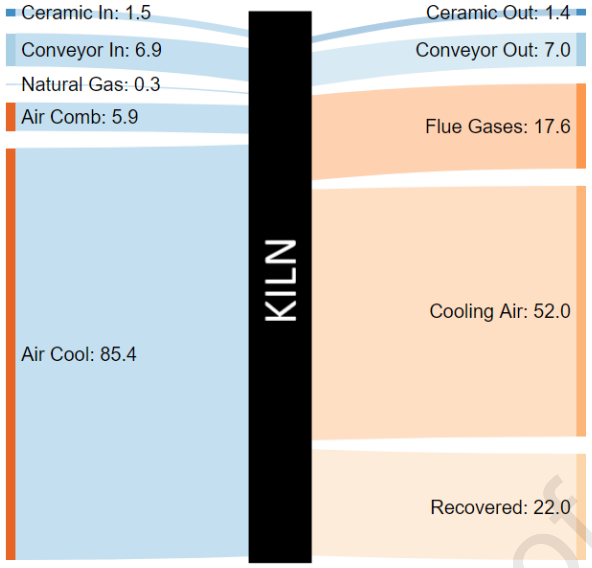

Figure 3 – Mass flow distribution (%) for Factory A.

4.2.2. Energy Balance

The energy analysis described in section 2 was applied and the results obtained are presented in Table A.2. The total energy at the entrance of the kiln is 1 716 kJ for A, 1 743 kJ for B and 1 491 kJ for C. The main energy fraction is associated with the NG, representing 85.7% to 90.5% of the total energy input. The energy flow associated with the cooling air also has a significant contribution, varying between 8.7% and 12.7% for the case studies. The energy inputs associated with the ceramic material, air combustion and conveyor belt/wagon are residual. Figure 4 shows a Sankey diagram with the energy balance for factory A (diagrams for B and C can be viewed in Appendix B).

Regarding the energy output, the flue and cooling exhaust gases are the most representative fractions, with 11.8% to 36.4% of the energy input being lost through the flue gas, and 38.3% to 61.0% lost through the cooling exhaust gas stack. There is some heat recovery (16.2% in factory A, 4.1% for B and 4.0% for C), which is used for pre-heating the combustion air (in the case of C) or the ceramic material inside the kiln (in the case of A and B). The losses which were not quantified result from the physical-chemical transformations of the ceramic material inside the kiln. Incomplete combustion of NG is also another factor that contributes to this fraction of energy. These losses were lower for factories A (7.3%) and C (7.9%), compared to B (14.0%). Ferrer et al estimate the energy needed to fire seven typical body compositions used in traditional ceramic manufacture [39], concluding that the reaction heat associated with the physical-chemical transformations can vary between 295 and 444 kJ·kg^{-1} of unfired tile. In factories B and C, these obtained values for the non-quantified losses are of the same order of magnitude as these values (344 and 431 kJ·kg^{-1}, respectively). For factory A it is significantly higher (702 kJ·kg^{-1}), which suggest there any issue with the NG kiln burners. Since the exhaust gases are diluted with air at the exit of the kiln, it is not possible to assess the efficiency of the NG burners.

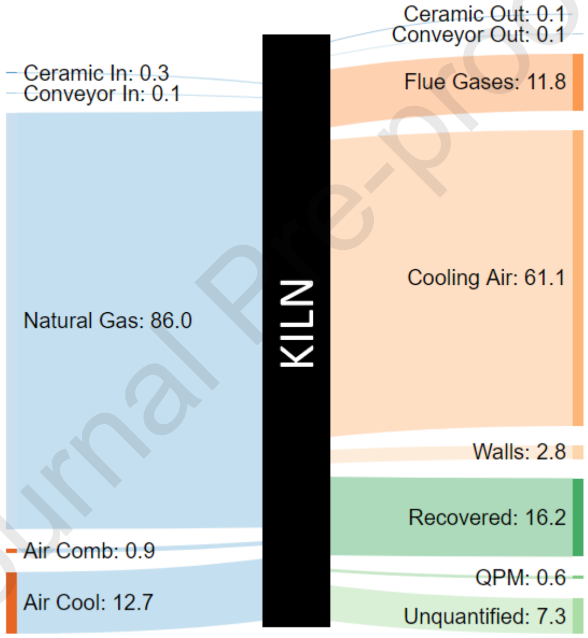

Figure 4 – Energy streams distribution (%) for Factory A.

On the other hand, the analysis of the total loss of variable energy by unit of production provides valuable insight into their impact to the ‘α’ parameter in the NG linear regression equation form section 4.1. The total variable energy loss is higher in factory A (7 747 kJ·kg^{-1}), followed by C (4 423 kJ·kg^{-1}) and B (2 179 kJ·kg^{-1}). these values validate the results obtained in the previous statistical analysis, in which ‘α’ was higher in factory C than in factory B. The greater the specific energy losses associated with the output flows from the kiln, the greater the ‘α’ value. Regarding the fixed energy term ‘E_0’, structural losses in the kiln are the main focus of inefficiency. The heat loss through the walls of the kiln are not significant in factory A (2.8%), while in B and C, the losses have a higher value (8.7% and 11.1%, respectively). In factories B and C, the temperatures measured by thermography on the external kiln walls suggest a possible degradation of the thermal insulation (T = 323 K), which can negatively affect the uniform temperature distribution in the interior of the kiln. The higher structural losses observed at factory C (166 kJ), compared to B (122 kJ), does not in itself explain the difference observed for ‘E_0’. Given that factory C has a continuous operation throughout the year, unlike factory B where the operation is not regular, it is expected that the kiln will have longer periods of empty operation, contributing to the higher value of ‘E_0’ observed in factory C. In the case of A, the low value of R^2 obtained in the regression equation for NG indicated possible anomalies in NG consumption, so the values obtained are in agreement with the results of the statistical analysis.

4.2.3. Performance Indicators

Table 5 shows the specific energy consumption of the kilns calculated from the energy balance (SEC) and based on annual data (SEC_a). The former reflects the performance of the kiln during the measurements period, while the latter is an indicator of the kiln performance throughout the year. Comparing these results with the best available technology for each type of ceramic product, kiln A presents a SEC (9 146 $kJ\cdot kg_{mat,out}^{-1}$) above the reference value. The SEC_a value is slightly higher (10 058 $kJ\cdot kg_{mat,out}^{-1}$), which confirms the low performance of the equipment. In the case of C, although the SEC result is inside the reference value, SEC_a is slightly lower (4 865 $kJ\cdot kg_{mat,out}^{-1}$). This result suggests that kiln C does not maintain constant operating conditions throughout the year, which impact its energy performance. In the case of B, the SEC (2 411 $kJ\cdot kg_{mat,out}^{-1}$) is inside the reference range value. However, as observed in the previous cases, SEC_a (4 862 $kJ\cdot kg_{mat,out}^{-1}$) is significantly higher, revealing an inefficient management of the material load in the kiln. These situations imply that the kiln is operating at a partial load, which negatively affects its energy performance.

Furthermore, it is of note that the specific consumption of the factory increases with operation time, which is also an indicator of efficiency loss over time. Lower efficiency is also synonymous with greater energy saving potential (S_P). The highest S_P value was obtained for factory A (68.7%), followed by factory C (21.5%) and B (9.6%).

The efficient use of energy in the oven also translates into low CO_2 emissions. The greatest environmental impact was obtained for factory A (607 $kgCO_{2e}\cdot ton_{mat,out}^{-1}$), as a result of the high energy consumption per unit of production. In contrast, factory B presented a satisfactory environmental performance, demonstrated by the low CI obtained (161.4 $kgCO_{2e}\cdot ton_{mat,out}^{-1}$). For the factories analysed, the CE associated with the firing stage is from B (25.9 $€\cdot ton_{mat,out}^{-1}$), with A (96.7 $€\cdot ton_{mat,out}^{-1}$) registering the highest value. In factory C, the energy cost associated with the firing stage is 53.3 $€\cdot ton_{mat,out}^{-1}$.

Table 5 – Specific energy consumption and energy cost of the firing stage.

	Factory A	**Factory B**	**Factory C**
Type of Kiln	Tunnel	Roller hearth	Tunnel
Age (Years)	38	14	27
SEC ($kJ\cdot kg_{mat,out}^{-1}$)	9 146	2 411	5 104
SEC_a ($kJ\cdot kg_{mat,out}^{-1}$)	10 058	4 862	4 865
SEC_{ref} ($kJ\cdot kg_{mat,out}^{-1}$) [40]	5 420 – 6 300	2 200 – 4 800	4 200 – 6700
S_P (%)	68.7	9.6	21.5
CI ($kgCO_{2e}\cdot ton_{mat,out}^{-1}$)	607.1	161.4	336.7
CE ($€\cdot ton_{mat,out}^{-1}$)	96.7	25.9	53.3

4.3. Energy Efficiency Measures

This section discusses measures and operating practices to reduce energy consumption in the production of ceramics. The measures are aimed at the most energy intensive equipment (kiln) and have the particularity of having zero or reduced implementation costs. To assess the potential impact of the measures, factory C is used as a reference in the analysis.

4.3.1. Ceramic Load

The mass and energy balances carried out for the kilns showed a tendency to operate at partial load. However, ceramic kilns are most efficient when their material load is equal or close to their rated capacity. A better understanding of the importance of this parameter can be obtained by analysing the regression equation discussed in section 3.1. By dividing the two sides of the equation by the ceramics production ‘P’, the following general formula for energy consumption is obtained:

$$\frac{\mathrm{E}}{\mathrm{P}} = \frac{\mathrm{E_0}}{\mathrm{P}} + \alpha \tag{22}$$

Although partial load operation has no influence on the ‘α’, it allows the dilution of the impact of ‘E_0’. If we consider that in factories with long periods of operation the ‘E_0’ value is high, one can conclude that the load optimization can result in significant energy savings. Based on the measurements made and the data provided by the engineering team at factory C, the consumption of NG as a function of production can be estimated by Equation 23. The coefficient of determination indicates the goodness of fit, showing that the consumption of NG in the kiln can be explained by the regression equation with high accuracy. The residual analysis that compares the predicted values of the regression equation with the measured values showed a low RMSE value, corresponding a mean absolute percentage error of 3.4%.

$$\mathrm{E_{NG}(GJ)} = 4.1 \cdot \mathrm{P} + 704.5 \tag{23}$$

$R^2 = 0.940$

RMSE = 109

Considering that the ceramic production capacity in kiln C is 1 125 $kg \cdot h^{-1}$, the impact that the partial load operation has on the operation of the kiln was estimated. Table 6 shows the results obtained, considering the continuous operation of the kiln during the period of one month. The operation of the kiln with a partial load of 50% can result in an increased consumption of NG by 17.5%. As the load increases, consumption per unit of production tends to decrease. However, the CE will always be higher than operating at nominal load. CI increases or decreases in the same proportion. It should be noted that the optimization of the kiln load is a measure of energy efficiency without any investment cost.

Table 6 – Performance parameters of kiln C as a function of material load.

Load (%)	NG (MJ/month)	SEC (kJ/kg$_{mat}$)	CE (€/ton$_{mat}$)	CI (kg$_{CO2e}$/ton$_{mat}$)	Δ_x (%)
50	2 366	5 841	57.3	374	17.5
60	2 698	5 552	54.5	356	11.7
70	3 030	5 344	52.4	343	7.5
80	3 363	5 189	50.9	333	4.4
90	3 695	5 068	49.7	325	1.9
100	4 027	4 972	48.8	319	-

4.3.2. Combustion in Gas Burners

Considering the intensive consumption of NG in the kiln, it is essential that its combustion is efficient. Maintaining a constant air to fuel ratio in the burners guarantees their proper function, maximizing the fuel conversion efficiency (FC). Checking and adjusting the air proportion in the NG burners is a simple and low-cost procedure, which can be carried out by elements of the engineering team or a specialized technician. The consumption of NG ($\Delta\mathrm{H_F}$) to obtain the energy input required by the ceramic kiln (E_{kiln}) as a function of FC, can be estimated from Equation 24.

$$\Delta\mathrm{H_F}\ (\mathrm{GJ}) = \mathrm{E_{kiln}} \cdot \frac{1}{\mathrm{FC}} \tag{24}$$

Using kiln C as a reference, the amount of thermal energy associated with NG was 1277 kJ. Assuming that this value relates to a complete conversion of the NG (FC = 1 and consequently $\Delta\mathrm{H_F} = \mathrm{E_{kiln}}$), we can assess the impact that incorrect operation of the burners has on the performance of the kiln. Table 7 shows the results obtained, considering a continuous operation of the kiln over a period of one month.

From the analysis of the results obtained, we can see that the uncontrolled burning of NG can result in significant energy losses. If a FC in the order of 0.75 is unlikely, values between 0.90 and 0.95 are easy achievable, which can result in an increase in energy consumption in the kiln between 5.3% and 11.1%. The CE associated with the production of ceramics and the resulting environmental impact increase in the same proportion. Therefore, providing a constant air to fuel ratio over the range of burner outputs will minimise the energy loss associated with NG combustion.

Table 7 – Performance parameters of kiln C as a function of fuel conversion.

FC (-)	**NG** (GJ·month^{-1})	**SEC** (kJ·kg$_{mat}^{-1}$)	**EC** (€·ton$_{mat}^{-1}$)	**CI** (kg$_{CO2e}$·ton$_{mat}^{-1}$)	Δ_x (%)
0.75	4 414	6 616	64.9	424	33.3
0.80	4 138	6 203	60.9	398	25.0
0.85	3 895	5 838	57.3	374	17.6
0.90	3 678	5 514	54.1	353	11.1
0.95	3 485	5 223	51.3	335	5.3
0.99	3 344	5 012	49.2	321	1.0
1.00	3 311	4 962	48.7	318	-

4.3.3. Heat Recovered from Cooling Air

During the firing stage a significant amount of low temperature waste heat is generated as result of the cooling of ceramic material and no recovery is performed. The low cooling air temperature (373–452 K) restricts the heat recovery capacity. Nevertheless, the drying stage allows for the integration of this energy fraction because the moisture reduction stage of the ceramic material is a low/medium enthalpy process, with temperatures between 323–623 K [40,41]. Contrary to the flue gases, for which the energy recovery requires additional costs (e.g. gas cleaning and heat exchangers systems), cooling air can be directly applied in the drying process.

At factory C, the drying process takes place at an average temperature of 343 K, requiring a hot air mass of 17.3 kg$_{air}$·kg$_{mat,out}^{-1}$. Considering the data in Table 4, the consumption of NG in the drying stage was 1009.5 kJ·kg$_{mat,out}^{-1}$. On the other hand, the cooling air in kiln C is 12.4 kg$_{air}$·kg$_{mat,out}^{-1}$ with an average temperature of 452K. Considering a recovery of a fraction of the cooling air (X_{rec}) for application in the dryer, we can estimate the energy savings (Δx) through Equation 25.

$$\Delta x\ (\%) = \frac{\text{Heat Recovered}}{1009.5} = \frac{X_{rec} \cdot 12.4 \cdot c_{p,air} \cdot (T_{cool} - T_{ref})}{1009.5} \times 100 \qquad (25)$$

Table 8 shows the potential energy savings for the drying process by direct use of cooling air, considering the recovery of different cooling air fractions. The values obtained reveal that there is a high potential for reducing energy consumption in the drying process, by heat recovery from the kiln cooling air. For the case study, the recovery of 30% of the cooling flow could result in energy savings in the order of 58%, resulting in a reduction in costs with NG from 9.9 to 4.1 €·$ton_{mat,out}^{-1}$.

Table 8 – Potential energy saving in drying stage with the recovered of air cooling.

X_{rec} (%)	**NG (GJ)**	**SEC (kJ·$kg_{mat,out}^{-1}$)**	**EC (€·$ton_{mat,out}^{-1}$)**	**CI (kg_{CO2e}·$ton_{mat,out}^{-1}$)**	**Δ_x (%)**
0	673	1 010	9.9	65	-
5	608	912	8.9	58	9.7
10	543	814	8.0	52	19.4
15	478	716	7.0	46	29.1
20	412	618	6.1	40	38.8
25	347	520	5.1	33	48.5
30	282	422	4.1	27	58.2

4.3.4. Comparison with other solutions

The main energy efficiency strategies presented in literature to increase the energy performance of kilns is based on waste heat recovery and kiln thermal insulation. A solution proposed by Caglayan et al. consists in using air from the cooling section of the kiln in the gas burners [20]. This measure can represent up to 4.7% of energy savings, which can be increase to 8-10 % if the air is further heated to 200-250 ºC. Others, such as Mezquita et al. propose a similar method, achieving up to 17% energy recovery [18]. Finally, Chuenwong et al. detailed studies that analysed energy savings from high efficiency burners (21%), repairing broken insulation (15%) or reducing heat leakage from kiln walls (23 – 30%) [36]. These strategies will always have some cost associated to them, ranging from 1 500€ for leak repairs, to 55 000€ for high efficiency gas burners. However, the presented solutions in this study reach similar results while having no investment cost.

5. Conclusion

The application of energy management systems in the Portuguese ceramic sector is essential to improve its performance and competitiveness. The statistical analysis, which relates the annual energy consumption with ceramic production, suggests an inefficient energy use, mainly for NG which represents 68% to 82% of the total energy consumption. The ceramic firing was identified as the critical stage in energy consumption. The SEC obtained for the kiln in factory A is above the reference value, while B and C have a SEC values within reference values. However, the calculated values based on annual data indicate that the kilns do not always operate in an efficient manner, negatively impacting the energy performance.

In the case of SMEs, kiln energy efficiency strategies should prioritize solutions that have little to no implementation cost. Therefore, this work shows that by applying no-cost energy efficiency measures, typical ceramic industries involving similar equipment and processes can significantly improve the energy performance of their manufacturing processes. The following strategies are proposed for enhancing kiln energy performance:

a) Optimisation of the ceramic load: ceramic kilns are most efficient when their material load is equal or close to their nominal capacity. The operation of the studied kiln with a partial load of 50% can result in an increased consumption of NG by 17.5%. As the load increases, consumption per unit of production tends to decrease.

b) Efficient NG combustion: maintaining a constant air to fuel ratio over the range of burner outputs guarantees their proper function, maximizing the fuel conversion efficiency. Uncontrolled burning of NG with a fuel conversion efficiency between 0.90 and 0.95 are easily achievable, which can result in increased energy consumption in the kiln between 5.3% and 11.1%.

c) Waste heat recovery: the energy analysis of the kilns showed an elevated amount of low temperature waste heat which is not integrated into the process (38-61%). Cooling air flows released from the kilns make waste heat recovery projects essential in the energetic optimization of ceramic production. The direct application of cooling air in the drying stage is a low-cost measure that can result in significant energy savings.

Although the studied factories are characteristic of the typical ceramic industry, this analysis is limited by the available data, since with only three factories, we cannot generalize about the efficiency of the entire sector with high certainty, as the method should first be applied to a wider range of facilities. Additionally, this analysis revealed that a partial load of the kiln can greatly affect the energy performance of the firing step. Therefore, future work should focus on extending the applied methodology to the entire factory to address the impact of partial load in all stages of manufacturing.

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Table A.1 – Characterization of input and output mass flows of the kilns studied.

	Flows	Parameters	Plant A	Xi (%)	Plant B	Xi (%)	Plant C	Xi (%)		Flow	Parameters	Plant A	Xi (%)	Plant B	Xi (%)	Plant C	Xi (%)
Mass Flows In	Natural Gas	$\dot{m}_F$ (kg·s^{-1})	0.033	0.28	0.035	0.28	0.028	0.30	**Mass Flows Out**	Flue Gases	$\dot{m}_{fg}$ (kg·s^{-1})	2.064	17.61	2.140	17.03	4.128	43.15
		T (K)	288		288		288				T (K)	365		513		397	
		W_w (%)	0.0		0.0		0.0				W_w (%)	1.0		0.9		0.9	
	Air	$\dot{m}_{comb}$ (kg·s^{-1})	0.709	5.96	0.756	6.13	0.563	5.92		Cooling Air	$\dot{m}_{cool}$ (kg·s^{-1})	6.101	52.07	8.471	67.41	3.233	33.79
		T (K)	300		293		353				T (K)	446		373		452	
		W_w (%)	0.8		0.8		0.8				W_w (%)	0.8		0.8		0.9	
		$\dot{m}_{cool}$ (kg·s^{-1})	10.15	85.39	10.54	85.53	7.97	83.91		Recovered	$\dot{m}_{rec}$ (kg·s^{-1})	2.569	21.92	0.990	7.88	1.296	13.55
		T (K)	300		293		300				T (K)	385		350		325	
		W_w (%)	0.8		0.8		0.8				W_w (%)	0.8		0.8		0.8	
	Ceramic	$\dot{m}_{mat}$ (kg·s^{-1})	0.179	1.51	0.711	5.77	0.286	3.00		Ceramic	$\dot{m}_{mat}$ (kg·s^{-1})	0.167	1.43	0.683	5.44	0.257	2.69
		T (K)	323		303		300				T (K)	313		303		313	
		W_w (%)	2.0		0.8		1.5				W_w (%)	0.0		0.0		0.0	
	Conveyor	$\dot{m}_{conv}$ (kg·s^{-1})	0.817	6.87	0.282	2.29	0.653	6.87		Conveyor	$\dot{m}_{conv}$ (kg·s^{-1})	0.817	6.97	0.282	2.24	0.653	6.82
		T (K)	305		303		300				T (K)	313		303		313	
	Total	$\sum \dot{m}$ (kg·s^{-1})	11.89	100	12.42	100	9.50	100		**Total**	$\sum \dot{m}$ (kg·s^{-1})	11.73	100	12.59	100	9.57	100

Table A.2 – Characterization of input and output energy flows of the kilns studied.

	Flows	Parameters	**Plant A**	Xi (%)	**Plant B**	Xi (%)	**Plant C**	Xi (%)
Energy Input	Natural Gas	$\Delta\dot{H}_F$ (kJ·s^{-1})	1 477.6	86.12	1 577.7	90.52	1 277.2	85.66
		Cp_F (kJ·kg^{-1}·K^{-1})	2.21		2.21		2.21	
		LHV (kJ·kg^{-1})	45 100		45 100		45 100	
	Air	$\Delta\dot{H}_{comb}$ (kJ·s^{-1})	15.2	0.88	10.8	0.62	42.4	2.84
		Cp_{air} (kJ·kg^{-1}·K^{-1})	1.014		1.014		1.017	
		h_{wv} (kJ·kg^{-1})	2 441		2 441		2 441	
		$\Delta\dot{H}_{cool}$ (kJ·s^{-1})	217.4	12.67	150.9	8.66	170.7	11.45
		Cp_{air} (kJ·kg^{-1}·K^{-1})	1.014		1.014		1.014	
		h_{wv} (kJ·kg^{-1})	2 441		2 441		2 441	
	Ceramic	$\Delta\dot{H}_{mat}$ (kJ·s^{-1})	4.7	0.28	2.9	0.6	0.6	0.04
		Cp_{mat} (kJ·kg^{-1}·K^{-1})	1.0		0.8		1.1	
	Conveyor	$\Delta\dot{H}_{conv}$ (kJ·s^{-1})	0.9	0.05	0.7	0.2	0.2	0.01
		$Cp_{c/w}$ (kJ·kg^{-1}·K^{-1})	0.16		0.48		0.16	
Total		$\sum$ In (kJ·s^{-1})	1 715.8	100	1 743.0	100	1 491.1	100

	Flow	Parameters	**Plant A**	Xi (%)	**Plant B**	Xi (%)	**Plant C**	Xi (%)
Energy Output	Flue Gases	ΔH_{fg} (kJ·s^{-1})	214.0	12.47	490.8	28.16	543.3	38.21
		Cp_{fg} (kJ·kg^{-1}·K^{-1})	1.128		1.139		1.115	
		h_{wv} (kJ·kg^{-1})	2 441		2 441		2 441	
	Cooling Air	ΔH_{cool} (kJ·s^{-1})	1 045.9	60.96	810.9	46.52	566.1	37.96
		Cp_{air} (kJ·kg^{-1}·K^{-1})	1.028		1.018		1.030	
	Recovered	ΔH_{rec} (kJ·s^{-1})	277.5	16.17	71.4	4.10	60.3	4.05
		Cp_{air} (kJ·kg^{-1}·K^{-1})	1.020		1.016		1.015	
	Ceramic	ΔH_{mat} (kJ·s^{-1})	2.5	0.14	2.7	0.15	4.0	0.27
		Cp_{mat} (kJ·kg^{-1}·K^{-1})	1.0		0.8		1.1	
	Conveyor	ΔH_{conv} (kJ·s^{-1})	1.9	0.11	0.7	0.04	1.6	0.11
		$Cp_{c/w}$ (kJ·kg^{-1}·K^{-1})	0.16		0.48		0.16	
Others	Walls	$\dot{Q}_S$ (kJ·s^{-1})	48.3	2.82	122.2	7.01	166.1	11.14
		T_s (K)	316		323		323	
	Unquantified	-	125.7	7.33	244.3	14.02	123.2	8.26
Total		$\sum$ Out (kJ·s^{-1})	1 590.0	100	1 498.7	100	1 367.9	100

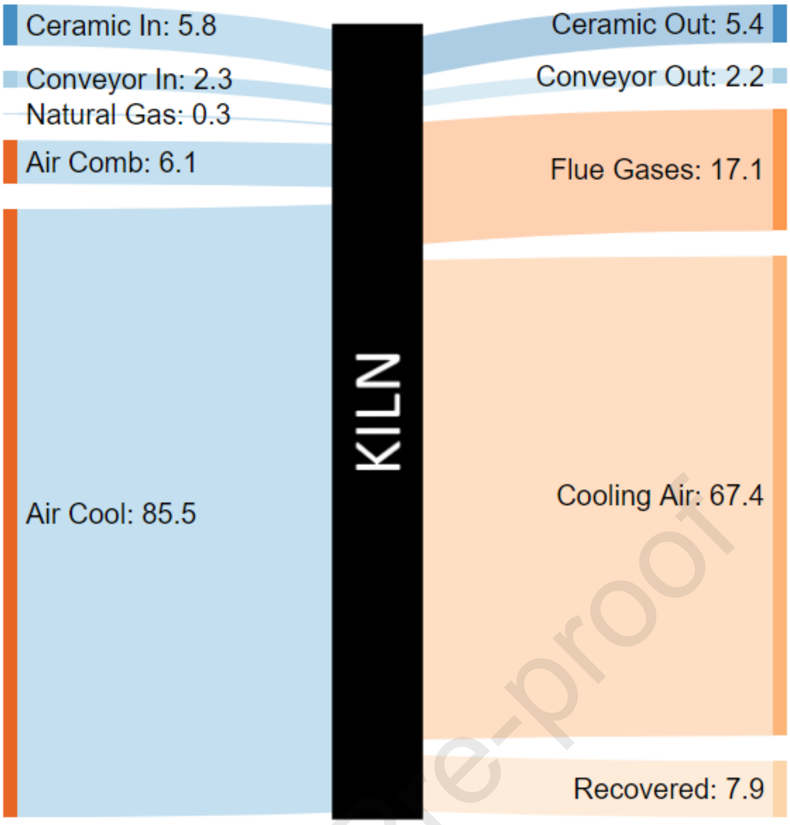

Figure B.1 – Mass flow Sankey diagram for Factory B.

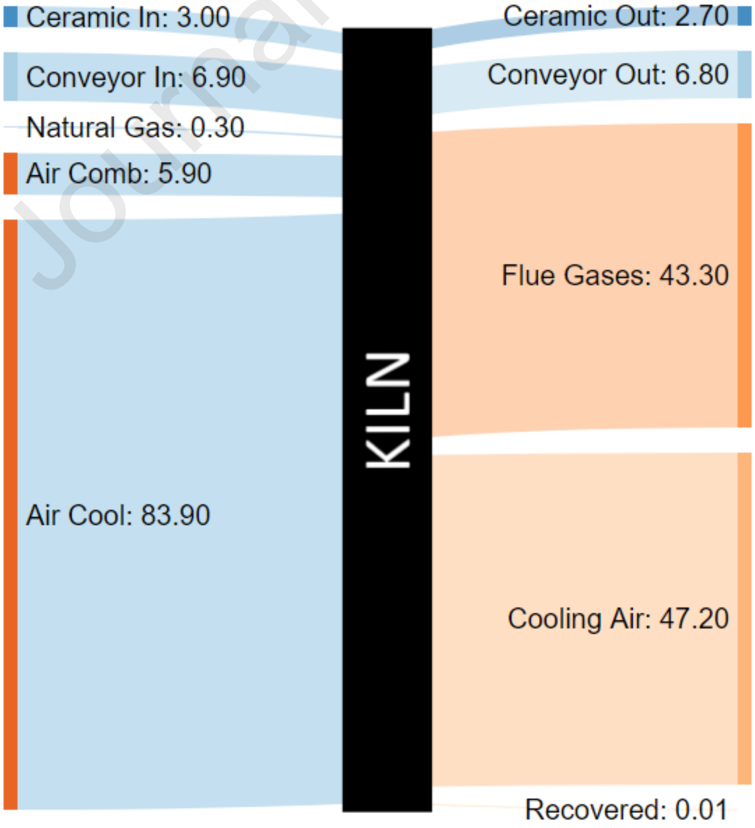

Figure B.2 – Mass flow Sankey diagram for Factory C.

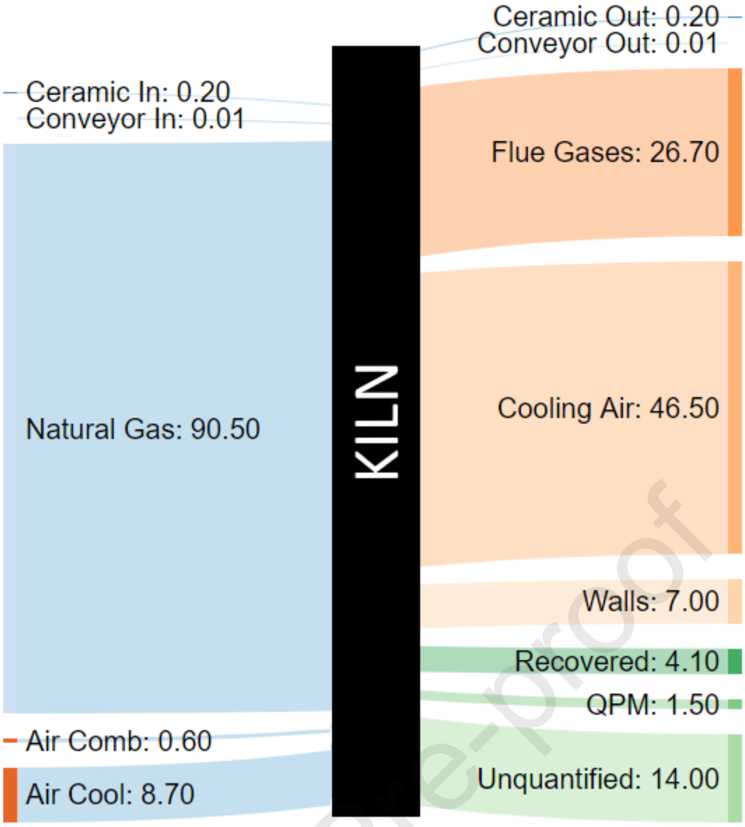

Figure B.3 – Energy balance Sankey diagram for Factory B.

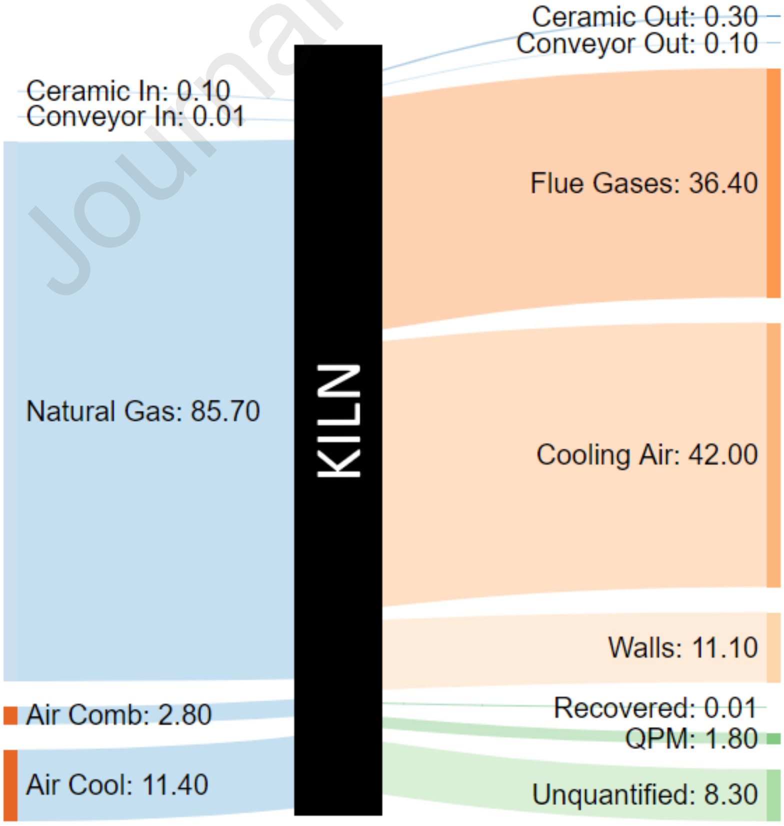

Figure B.4 – Energy balance Sankey diagram for Factory C.

HIGHLIGHTS

- No-cost energy efficiency strategies were evaluated.
- Statistical and thermodynamic analysis was performed.
- Inefficient energy management was observed, with a particular focus on natural gas.
- Optimization of ceramic load can decrease energy consumption by 2 to 18%.
- Combustion in gas burner can achieve 1 to 11% energy savings.

Luís Carlos Marques Ruivo (Luís Ruivo): Conceptualization, Methodology, Investigation, Formal analysis, Visualization, Validation, Writing - original draft, Writing - Review & Editing.

Michael Anthony Martins Tavares Russo (Michael Russo): Conceptualization, Methodology, Investigation, Formal analysis, Visualization, Validation, Writing - original draft, Writing - Review & Editing.

Rúben Borges Lourenço (Rúben Lourenço): Conceptualization, Methodology, Investigation, Formal analysis, Writing - Review & Editing.

Daniel Torrão Pio (Daniel Pio): Conceptualization, Visualization, Writing - Review & Editing.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: