ENERGY PERFORMANCE LEVEL ANALYSIS OF A BRICK MANUFACTURING PROCESS

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Abstract: Brick manufacturing processes are energy-consuming processes which justify the concerns for identifying their level of energy performance (EP) and establishing measures to increase energy efficiency. The level of energy performance stands out through established indicators, mainly, specific energy consumption. This paper represents a synthesis of an energy audit (EA) conducted on "poroton" type brick manufacturing process, from a factory equipped with two tunnel type ovens. In the first part are highlighted energy-related characteristics of the process. Next, is presented analysis method, including the specificities of energy balance (EB) model. A good portion of paper is dedicated to present the results obtained therefore the level of energy performance. The final part contains the conclusions of analysis and recommendation regarding improvement of EP.

Keywords: energy performance, brick, indicators, optimization

1. INTRODUCTION

Brick manufacturing processes (BMP) are included in "ceramics" industry along with tiles, fine ceramics, sanitary stoneware and similarly [1]. Worldwide, most of "ceramics" factories are located in China, India, Pakistan and Bangladesh [1]. Worldwide "ceramics" industry is credited with a 5.87% of total electricity consumed in industry [2]. Locally, at a national level, without having reliable data regarding the weight of energy consumption in "ceramics" industry we mention that in terms of the scale of the civil and industrial buildings, in Romania, which uses bricks and energy-intensive characteristics of BMP, these processes are important under the terms of EA. At worldwide level, mainly, there are five brick manufacturing technology [1], one of them being "tunnel kilns" – frequently used in Romania which is the subject of the analysis that we summarize in this paper. To emphasize the importance of preoccupation, we mention that worldwide BMP are likely to increase with 15-50% in developing countries like Romania [1].

Besides the considerations mentioned above, the preoccupation summarized in this paper fits in the general arguments of necessity and utility of EAanalysis[3 ÷ 8]. The present paper synthesizes EA of a BMP from a poroton brick factory (PBF) equipped with 2 tunnel type ovens.

Technological flow diagram – specifying the phases and energy carriers which are used is presented in figure 1.

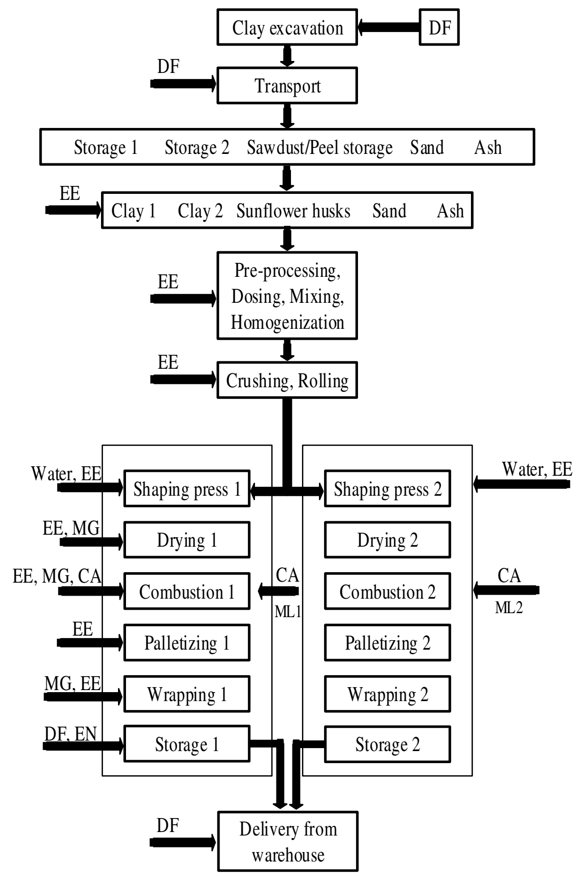


Fig. 1 - Technological flow diagram of PBF where MG – methane gas; EE – electric energy; DF - diesel fuel; CA – compressed air

Bricks are dried in two tunnel dryers (TD) and the burning in two tunnel ovens (TO). In figure 2 is presented a principle diagram of this zone (thermoenergetical) from a manufacturing line (ML) of PBF.

Tunnel ovens are aggregated to burn ceramic products, built from refractory bricks, insulating material and padded on the outside with metal sheet. The dimensions of a TO from PBF are: L = 110m; W = 6m; h = 3m. The oven is divided in three areas (zones) accordingly to diagram from figure 3.

Methane gas (MG) is supplied in burning area (zone) through 44 burners, for each TO, mounted on each side.

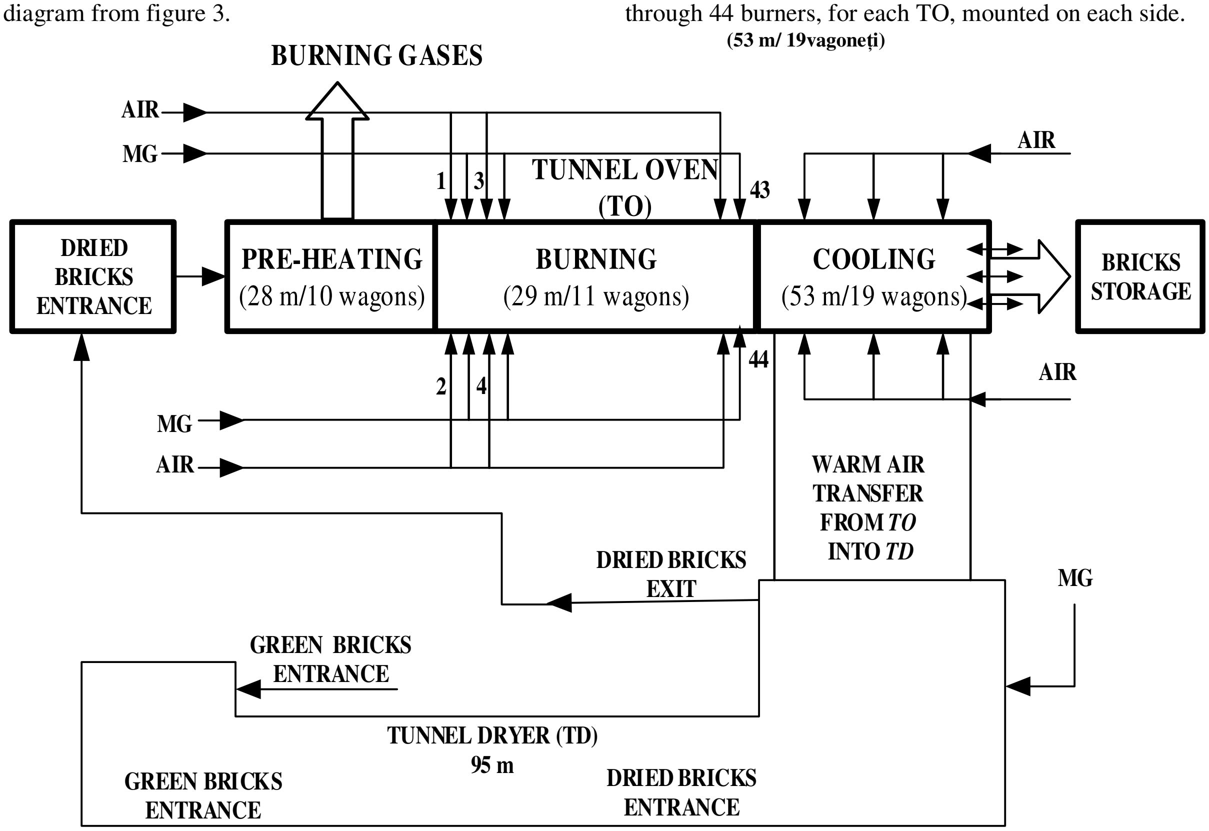


Fig. 2 – Principle diagram of a thermoenergetical zone from a manufacturing line (ML) of PBF

Flue gasses circulates in countercurrent with the products, the evacuation of gasses takes place in preheating area so their heat is transferred to old material, newly inserted in oven. The evacuation of flue gasses is carried through chimney located at the cold end (preheating zone) of each TO. The chimneys are 12 m tall. The discharge of flue gasses is performed with a fan. In order to monitor gas emissions into the atmosphere, the chimney has an indentation where is mounted the sampling rod. Most of the warm air used in the TO is transferred in the form of reusable energy resource (RES) toward dryer (figure 2).

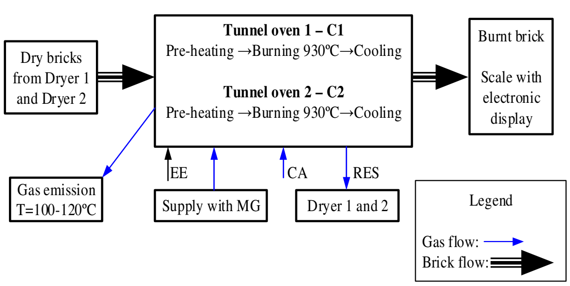


Fig. 3 – Principle diagram for brick burning process in TO - PBF

Energy flow floated in PBF contour is composed by: EE, MG and DF. MG is the most important energy carrier – in term of the weight in technological process being used to produce thermal energy required to dry and burn the bricks in TD and TO. It is used also for wrapping, preparation of thermal agent used for heating and preparation of domestic hot water.

EE consumption occurs in the main processes for the production of finished products from refractory materials – bricks; transport of raw materials from silos to processing line; material preparation; heat treatment control and packing processes. EE is also consumed in a significant proportion, in a range of auxiliary processes like: compressed air production, thermal agent distribution, indoor and outdoor lighting, ventilation, pumping…etc.

DF is used by vehicles, equipment and machinery for excavation, transport and raw material manipulation (clay, sand…etc.) from exploitation/acquisition area to PBF. In 2018, level of energy consumption and the weight of these 3 energy agents was:

- MG: 6089.57 toe (88.8%);
- EE: 649.13 toe (9.47%);
- DF: 117.03 toe (7.73%).

Economic value of PBF production was, in 2018, 6,650thousandeuro, the share of energy in production costs was 34.15%. The physical value of the production in the same year, was 174835 tons.

2. WORKING METHODOLOGY

2.1. Analysis steps

To perform the analysis of the level of energy performance of industrial processes, well-known steps are followed [9 ÷ 13]:

- Identification of the energy consumer in terms of technology and energy;
- Selecting and - if necessary- adjusting and completing of energy balance (EB) mathematical mode;
- Establishing the list of quantities of which values are necessary to apply the EB model, mean of identification and measuring instrumentation;
- Conducting the measurements and completion of documentation with quantities values which are used in EB equations;
- Evaluation of EB components;
- Energy performance indicators (EPI) evaluation;
- Comparison of EPI with values published for similar processes (benchmarks);
- Establishing the means to improve energy efficiency (MIEE) and characterize them under technical and economic aspects;
- EPI estimation under the assumption of economically feasible application of MIEE.

We mention that, with reference to PBF in tunnel kilns, as presented in this paper, EPI most important - specific energy consumption – is given in two technological versions: Best Practice Technology (BPT) and Best Available Technology (BAT).

The essential elements of identification of analyzed consumer,which is PBF, is presented in chapter one of paper. In this frame we will present the specificities of EB mathematical model (EBMM) and to evaluate EPI, as fundamental component of working methodology. Considering the involved energy agents in BMP (figure 1), the developed EB is a complex one (CEB) with a thermo-energetic part (TEB) and an electro-energetic part (EEB). EB models are developed and widely implemented [9÷23], but – equally – lend themselves to adjustments or/and additions which are considering the specificities of processes and installations to which it refers. In this frame we'll present only the specific part.

TEB refers to the whole (TD+TO) – thermo-energetic equipment with continuous operation. Since this two equipment are not physically linked nor technological coupled, there is a dried brick warehouse among them, we'll refer to both equipment.

2.2. The general TEB equation

2.2.1. General equations of TEB at TO

a) **General equations:**

$$\sum W_I = \sum W_U + \sum W_P + \sum W_{tU} \quad (1)$$

where:

$\sum W_I$ - sum of quatities entered in contour;

$\sum W_U$ - sum of quantities of useful energy ;

$\sum W_P$ - sum of energy losses;

$\sum W_{tU}$ - the energy transmitted to the dryer (SER - secondary energy resource)"

b) **Energy go into TO contour**, mainly on the following ways:

- Fuel energy (Heat) (Q_c);
- Sensible heat of material that has entered in TO(Q_{sm});
- Heat of the air entered (Q_{ae});
- Heat produced on the inside, through exothermic reaction (Q_{ex});

So,

$$\sum W_I = Q_c + Q_{sm} + Q_{ae} + Q_{ex} \quad (2)$$

c) **Useful energy of TO**has the following components:

- Sensible heat of main product (Q_{pp}) – brick;
- Heat consumed for evaporation of moisture and of water of crystallization (Q_{ev});
- Sensible heat of mechanism who carry the bricks (Q_{mc});

so,

$$\sum W_U = Q_{PP} + Q_{ev} + Q_{mc} \quad (3)$$

d) **Energy losses within TO** can be grouped by category as follows:

- Sensible heat of flue-gases evacuated at chimney (Q_{ga});
- Sensible heat of warm air which is evacuated at chimney (Q_{acc});
- Heat lost with flue-gasses through leakage, doors opened and holes (Q_{go});
- Necessary heat to heat up the water vapor from air introduced in OT (Q_{au});
- Radiant heat through leakage, doors and holes opened (Q_{ro});
- Heat lost through radiation and convection of heated surfaces, toward environment (Q_{rc}).

So,

$$\sum W_P = Q_{ga} + Q_{acc} + Q_{go} + Q_{ro} + Q_{rc} + Q_{au} \quad (4)$$

Method of calculation of TEB for TO are presented in [13,24].

Reference unit adopted for this TEB is [kJ/t]. Finally, we will evaluate the values of the TEB components, in [toe/t] respectively [toe] for physical value of the production (V_{FP}), made in the analyzed time (τ)

2.2.2 TD's TEB model

The general TEB equation for TD

$$\sum W_I = \sum W_u + \sum W_P \quad (5)$$

In this case:

$$\sum W_I = W_u + W_{cu} + Q_{mu} + Q_{exu} \quad (6)$$

where:

(Q_{cu}, Q_{mu}, Q_{exu}) - have the same meaning as similar quantities for TO (Q_c, Q_m, Q_{ex}) are calculated with the specific relations, using the quantities from the dryer.

$$\sum W_u = Q_{ppu} + Q_{evu} + Q_{mcu} \quad (7)$$

where:
(Q_{ppu}, Q_{evu}, Q_{mcu}) have the same meaning as similar quantities for TO (Q_{pp}, Q_{ev}, Q_{mc}) are calculated with the specific relations, using the quantities from the dryer.

$$\sum W_P = Q_{rcu} + Q_{agu} \quad (8)$$

where:
Q_{rcu} - the heat lost by radiation and convection of TD surfaces - is calculated with a relation similar to that of TO.

The BT components for TD are calculated according to the established MMBE [13, 24].

2.3. The general EEB equation

For the analyzed contour the EEB equation is:

$$W_a = W_{UE} + \Delta W_T + \Delta W_L + \Delta W_M + \Delta W_{IL} \quad (9)$$

where:
W_a - energy absorbed by PBF, on the analyzed contour, determined on the basis of records, in the analysis interval [τ]; [MWh].
ΔW_T - EE losses on transformers;
ΔW_L - EE losses on power lines;
ΔW_M - EE losses on motors and mechanisms driven by contour;
ΔW_{IL} - EE losses on luminaires.

Based on equation (9) the useful energy (W_{UE}) is calculated at the level of the receivers.
The components of EEB are calculated according to the established MMBE [9 ÷ 13, 22].
The components of EEB, during the analysis [τ] obtained in [MWh], are transformed into [toe] using the relation:

$$(W, \Delta W)[MWh] = 0{,}086\ (W, \Delta W)[toe] \quad (10)$$

2.4. Energy performance indicators (EPI)

By accepting the established methodology, in this case, the EPI evaluation can be done at levels:
• The oven itself (TO) - based on BTE;
• Oven + dryer - based on TEB;
• Limited manufacturing line (inside the hall) - LML comprising TO, electromechanical equipment and electrical installations, based on ATE and AEE results;
• The factory with the two extended manufacturing lines (EML = LML + the equipment outside the hall, used for the extraction and transport of raw materials).

When calculating the indicators, the forms of energy involved (thermal, electrical, fuels used) are introduced with the same unit of measurement (toe). We will evaluate the indicators:

2.4.1. Net energy efficiency

- At TO level:

$$\eta_{nct} = \frac{\sum W_U}{\sum W_I}\ 100\ [\%] \quad (11)$$

- At TO + TD level:

$$\eta_{nCU} = \frac{\sum W_{UC} + \sum W_{UU}}{\sum W_{IC} + \sum W_{IU} - W_{tU}} \quad (12)$$

- At LML level:

$$\eta_{nLML} = \frac{\sum(W_{UC} + W_{UU}) + c_{ML} \cdot W_{UE}}{\sum(W_{IC} + W_{IU}) + c_{ML} \cdot W_a - W_{tU}}\ 100\ [\%] \quad (13)$$

- AtPBF level:

$$\eta_{nPBF} = \frac{\sum(W_{UC} + W_{UU}) + W_u + W_{uMT}}{\sum(W_{IC} + W_{IU}) + (W_a + W_{DF}) - W_{tU}}\ 100\ [\%] \quad (14)$$

where:
c_{ML} – the share of the total consumption of EE, respectively fuel, related to the analyzed ML;
W_{DF} - additional energy consumption, related to the fuel consumed for extraction and transport of raw materials, as well as inside the PBF;

2.4.2. Specific energy consumption:

• At TO level (specific methane gas consumption):

$$c_{nTO} = \sum \frac{W_I}{V_{FP}} \left[\frac{toe}{t}\right] \quad (15)$$

• At TO + TD level:

$$c_{nCU} = \frac{\sum W_{IC} + \sum W_{IU} - W_{tU}}{V_{FP}} \left[\frac{toe}{t}\right] \quad (16)$$

• AtLML (MG + EE) level:

$$c_{nLML} = \frac{\sum(W_{IC} + W_{IU}) + c_{ML} W_a - W_{tU}}{V_{FP}} \left[\frac{toe}{t}\right] \quad (17)$$

• AtPBF (MG + EE + CB) level:

$$c_{nPBF} = \frac{\sum(W_{IU} + W_{IC}) + W_a + W_{DF} - W_{tU}}{V_{FP}} \left[\frac{toe}{t}\right] \quad (18)$$

2.4.3 Share of EE consumption in total consumption:

• At LML level:

$$P_{ELML} = \frac{c_{ML} W_a}{\sum(W_{IC} + W_{IU}) + W_a - W_{tU}}\ 100\ [\%] \quad (19)$$

• At PBF level:

$$P_{EPBF} = \frac{W_a}{\sum(W_{IU} + W_{IC}) + W_a - W_{DF} - W_{tU}}\ 100\ [\%] \quad (20)$$

2.4.4. Energy intensity:

- At TO level:

$$I_{WTO}=\frac{\sum W_I}{V_{EP}}\left[\frac{toe}{MU}\right] \tag{21}$$

- At TO + TD level:

$$I_{WCU}=\frac{\sum(W_{IC}+W_{IU})-W_{tU}}{V_{EP}}\left[\frac{toe}{MU}\right] \tag{22}$$

- At LML level:

$$I_{WLML}=\frac{\sum(W_{IC}+W_{IU})+c_{ML}W_a-W_{tU}}{V_{EP}}\left[\frac{toe}{MU}\right] \tag{23}$$

- At PBF level:

$$I_{WPBF}=\frac{\sum(W_{IC}+W_{IU})+W_a+W_{DF}-W_{tU}}{V_{EP}}\left[\frac{toe}{MU}\right] \tag{24}$$

2.4.5 Energy productivity:

$$p_W=\frac{1}{I_W}\left[\frac{MU}{toe}\right] \tag{25}$$

MU – monetary unit (EURO, USD… etc.)

It can be calculated at the four levels. The indicators (I_w, p_w) will also be calculated in [kWh/MU; MU/kWh].

3. RESULTS OF THE MEASUREMENTS

The presentation of measurements and other input data is structured on the two categories of EA.

3.1. Data and measurements for ATE

TO subjected to ATE is intended for the combustion of refractory products - in this case brick - and has the characteristics shown in table 1, being divided into 3 zones (fig.2):

Table 1 - Technical-functional characteristics of TO-PBF

No.	Characteristics	M.Us.	Value
1.	Productivity in operation	t/day	393,45
2.	Burning temperature: • maxim • average (measured)	°C	940 841.3
3.	Fuel consumption during the measurement period	kWh/t	283.1
4.	Burners with air: • number • Pressure	pcs. bar	44 1.2-1.5
5.	Cycle time	Hours	23
6.	Constructuve features: • length • width • height • Useful volume • Number of wagons	m m m m^3 pcs.	110 6 3 1750 40
7.	Wagon load (brick)	t	9.43

TO operation is continuous. The BTE contour comprises the entire TO, as well as the dryer (TD) corresponding to the same ML, in which the drying phase of the brick is performed (fig.2). The TD characteristics are shown in Table 2.

Table 2 - Technical-functional characteristics of TD-PBF

No.	Characteristics	M.U.	Value
1.	Productivity (dryed brick)	t/day	444.6
2.	Drying temerature: • maxim • average	°C	81.1 51.3
3.	Burners with MG: • number • pressure	pcs. bar	1 1.2 ÷1.5
4.	Fuel consumption	kWh/t	21.4
5.	Cycle time	hours	48
6.	Constructuve features (interior): • length • width • height • useful volume • number of trolleys	m m m m^3 pcs.	95 17 4.5 6180 228
7.	Average load on a trolley (brick)	t	4.27
8.	Trolley mass	t	1.3
9.	Brick humidity dispated in TD	%	15.86

In the time interval in which the measurements were performed, dedicated to the elaboration of AEC, only old manufacturing line (OML) functioned, at normal capacity, producing POROTON type brick, with dimensions 290 x 245 x 238.

This brick has the following composition:

- Clay: [75 – 64] %;
- Sand: [15 - 25] %;
- Ash: [5 - 6]%;
- Sunflower husks: 5%.

Such a brick, in green condition (at the entrance to the dryer) has the mass: m_{cv} = 15.45 kg.

On a trolley entering the TD are placed a number of N_{cv} = 300 - raw bricks.

At the exit of the TD, a dry brick has a mass: m_{cu} = 13 kg.

This brick is loaded on the wagons that will enter the TO, the wagons lined with refractory brick that have other dimensions than the wagons that enter the TD. On a wagon that enters the TO is loaded a number of Ncc = 744 - dry bricks with mass mcu. At the exit of the TO, a burnt brick has a mass of mca = 12.34 kg.

To perform ATE it is necessary to know the variable quantities highlighted in the balance equations.

Fuel consumption - MG, during the measurements, is shown in fig. 4.

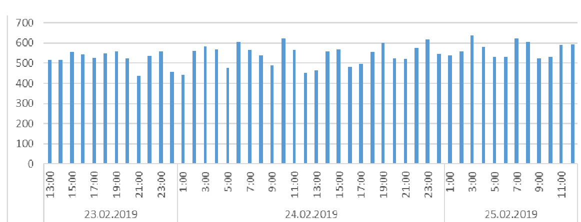


Fig. 4 – Graphical representation of PBF-MGconsumptiondurring the measurements

The average value of MG consumption for the measurement period was 543.167 m3 / hour. For the evaluation of the TEB components, we consider the fact that 10.5 kWh corresponds to one cubic meter of MG.

MG consumption for the last 3 years and for each month in 2018 is shown in Table 3.

Table 3 - Recent energy consumption of PBF

Energy agent / Year/month	Natural gas (MG) [MWh]	Electricity (EE) [MWh]	Diesel fuel (DF)[t]	TOTAL [toe]
2016	40,352	4,473	130	3,986.9
2017	47,587	5,026.3	120	4,646.54
2018	70,809	7,548	115.3	6,855.73
01	3	14.4		
02	2,319	274		
03	5,835	626		
04	6,806	667		
05	7,415	727		
06	6,599	742		
07	7,122	761		
08	7,875	792		
09	7,558	790		
10	8,322	895		
11	8,188	886		
12	3,105	374		

MG consumption is mainly intended for the process of burning bricks with a distribution of the following type:

- Tunnel oven (TO): 81%;
- Dryer (TD): 18%;
- Wrapping: 0.90%;
- Heating (boiler): 0.10%.

Using a **Ti20-Fluke infrared thermometer**, temperature measurements were performed at significant points for TO and TD ATEs. We show in table 4, the average values of the measured temperatures, and in fig. 5, for example, an image taken with the thermal imaging camera.

Table 4 - Temperature values measured during the study period

Nr. crt.	Area	θ_{med} [°C]
1	TO entrance door	24.1
2	Side surface preheating area TO	29.1
3	The lateral surface of the combustion zone TO	35.77
4	Lateral surface of the TO cooling zone	31.47
5	TO exit door	15.5
6	Top surface (vault) of the TO - cooling zone	40.15
7	The upper surface (vault) of the TO - the burning area	39.37
8	Top surface (vault) of TO - preheating zone	27.83
9	TD entrance door	25
10	The lateral surface of the TD	26.5
11	TD exit door	40
12	The dome of TD	30
13	Brick - at the entrance to TD	28.9
14	Brick - at the exit of TD	77
15	Brick at the entrance to the TO	30.2
16	Brick - when leaving the TO	20
17	Brick - at least 10 min. from the exit of the TO	26.35
18	Wagons for TO (in the hall)	37.55
19	The chamotte on the wagons - (in the hall)	37.5
20	In the hall (environment)	21
21	Steam released into the atmosphere	37.9
22	TDchimney	28

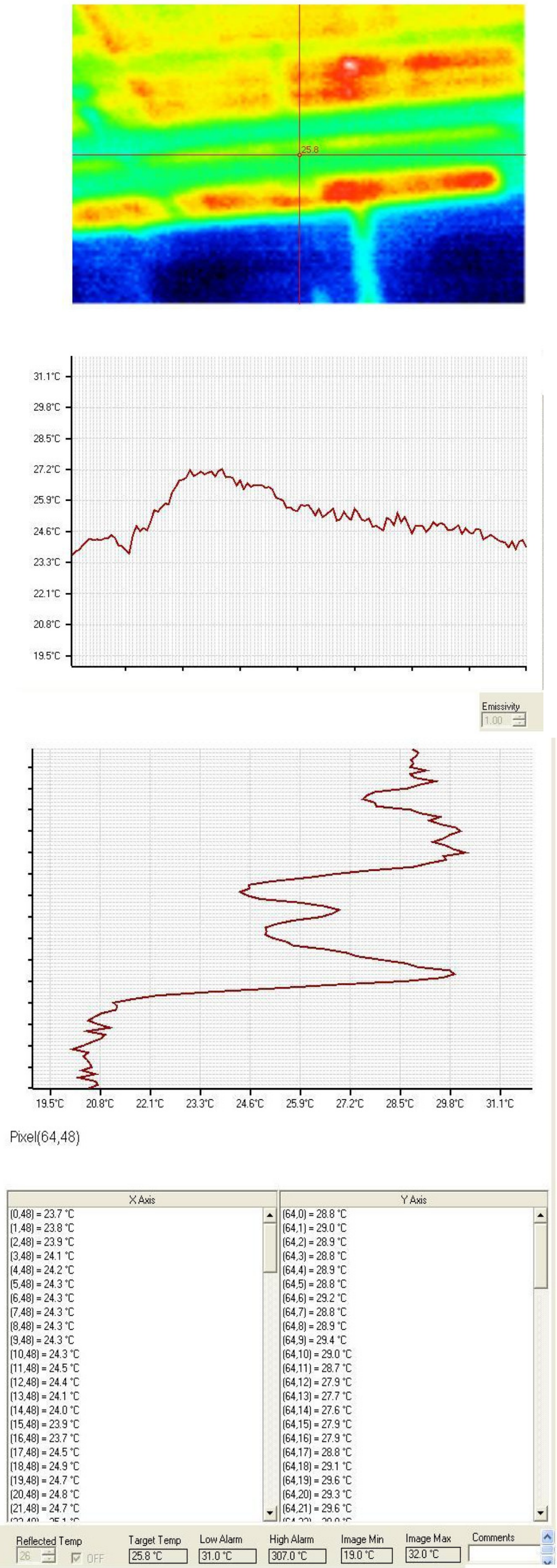


Fig. 5 - Brick thermographic image at the time of exit

Using the PBF monitoring system, temperature values were recorded at significant points inside TO and TD (Table 5).

Table 5 – Temperature values at significant points inside TOandTD

Nr. crt.	Equipment	Area	θ med [°C]	
			Reference	Measured
1	Tunnel oven (TO)	Preheating	455	412
		Combustion	853	841.25
		Cooling	517.5	511.1
2	Tunnel dryer (TD)	Entry area		38.45
		Exit area	85	81.1
		Intermediate area		48.9

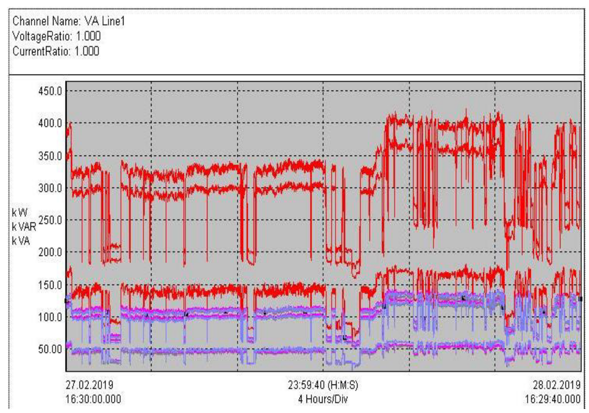
Other information required for the application of MM of TEB to TO is given in table 6.

Table 6 - Quantities measured at TO

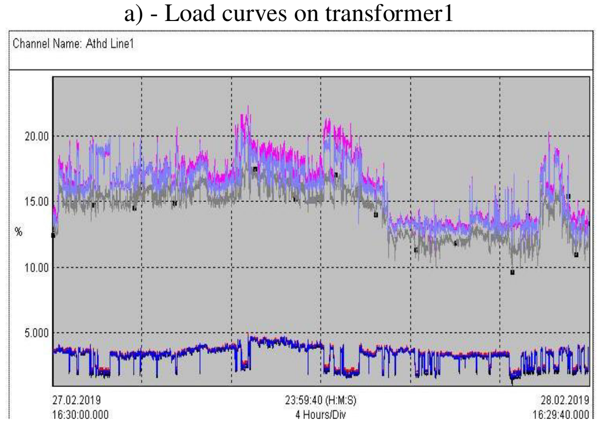
Quantity	Symbol	M.U.	Value
1	2	3	4
Number of bricks (per day)	V_{FP}	t/zi	393.45
Fuel (per day)	D_C	m^3_N/zi	10,559.16
The calorific power of NG	q_e	kJ/ m^3_N	37,980
Amount of clay for bricks (per day)	G_{mp}	t	383.21
Fuel composition: • oxygen • nitrogen • methane gas	O_2 N_2 CH_4	%	0.5 1.5 98
Fuel temperature	θ_c	°C	21
Temperature of brick when entering TO	θ_{sm}	°C	30.2
Cycle time	τ_c	ore	23
The temperature in the hall	θ_a	°C	21
Temperature inside TO	θ_{TO}	°C	table 5
Temperature at the outer surface of the TO	θ_p	°C	table 4
Composition of materials entered in TO (one day): • dry brick • humidity • the mass of a wagon (metal + chamotte) • the metal part of a wagon	Gcăr W1+W2 Gu Gc	t % t t	403.7 5.07 1.5 0.4
Temperature of wagon when entering TO	θ_{sm}	°C	30.2
Combustion air temperature (at entry)	θ_L	°C	22
Cooling air flow blown into the oven: • in the cooling zone • in the combustion zone	D_1 D_2	m^3/h m^3/h	47200 5500
Cooling air temperature (inlet)	θ_{ar}	°C	22
Duration of measurements	τ_{ms}	h	120
Brick temperature when exiting TO	θ_{mc}	°C	26
Temperature of the wagons when exitingTO	θ_{ve}	°C	37.5
Refractory liner temperature at TO exit	$\theta_{căpt}$	°C	37.5
Flue gas temperature in the combustion zone	θ_{go} ,θ_{ga}	°C	841
Hot air temperature in the oven	θ_{ac}	°C	511
Flue gas analysis:	HCl	mg/Nm^3	2.1
	CO NO_x SO_2		206.19 45.89 4.1
Flue gas flow out of the oven	D_{ga}	m^3/h	43,920
Flue gas flow out of the furnace	$\theta_{g,coş}$	°C	112
Hot air flow transferred to TD	D_{ac}	m^3/h	45,700
Number of TO holes	n	buc.	44
The middle section of the hole	S_o	mm^2	175
Average opening time of the hole	τ_o	h/τ	0.5

3.2. Data and measurements for EEB

EE consumption in the last 3 years is shown in Table 3. Using the Network Analyzer (AR), EE consumption and EE quality were recorded on the main equipment and installations in the PBF structure. Since, during the study period, only one production line operated, the results of the records reflect the related consumption only for this. For example, in fig. 6 shows the records on transformer 1.



a) - Load curves on transformer1



b) –THD variation

Fig. 6 – AR records on transformer 1

3.3. Other information required for EPI calculation

For the evaluation of EPI are used - on the one hand - energy consumption distributed by components and - on the other hand, production. Table 7 shows the value of production in the last 3 years. The value of production during the analysis period (24 hours) is listed in Table 8.

Table 7 - Recent production of PBF

Year / month	Phisical value of the production (V_{FP}) [t]	Economic value of the production (V_{EP}) [mii euro]
2016	111,710	3,848
2017	124,140	4,223
2018	174,835	6,652
01	0	0
02	3,840	150.4
03	11,838	463.6
04	16,473	645.2
05	18,322	717.6
06	17,297	677.5
07	19,442	761.5
08	21,079	825.6
09	19,560	766.1
10	20,607	807.1
11	19,554	765.9
12	6,823	267.2

4. RESULTS OBTAINED WITH REGARD TO REAL CEB

Based on the measurements performed, the calculation quantities taken from the analysis bulletins and from the database provided by the beneficiary, using the CEB models, the numerical values of the CEB components were determined. This chapter presents a summary of the results obtained, structured on the two components (TEB, EEB)

4.1. Real EBconsideringthe load recorded during the measurement period

The synthesis of the obtained results is presented in the EB diagrams (fig. 7 ÷ 9).

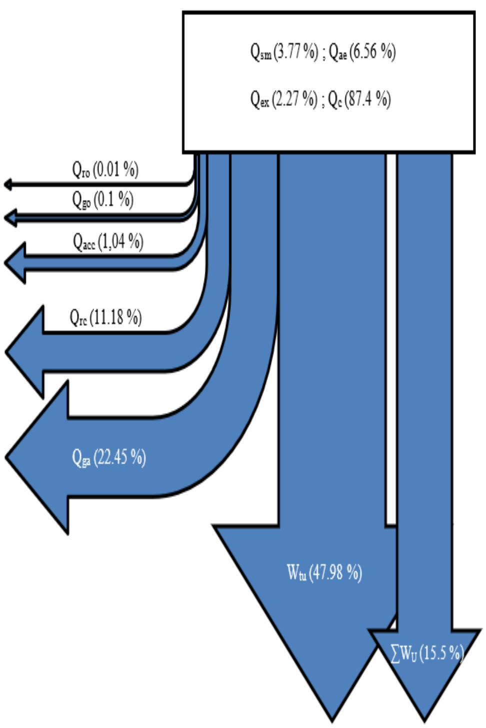


Fig. 7 - Sankey diagram of real TEB, daily, for TO-PBF [stabilized load]

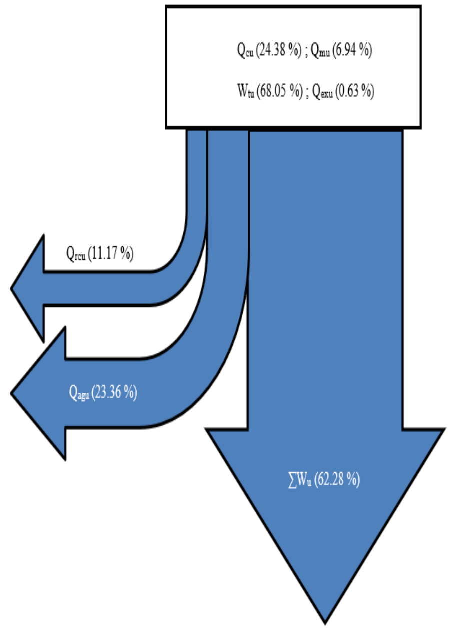


Fig. 8 - Sankey diagram of real TEB, daily, for TD - PBF [stabilized load]

The following records show the following average distribution of EE consumption within the PBF.
Of the total consumption:

- About 94% - is consumed in the effective technological processes of brick production;
- About 6% - is consumed for additional processes and activities necessary for the operation of the PBF.

A hierarchy of equipment serving PBF, depending on the average value of the absorbed active power, can be done as follows:

- Ventilation management for the dryer (including hot air transfer from TO): 31.5%;
- Crushing + rolling + shaping (press): 24.7%;
- Pre-processing: 16.3%;
- Ventilation management for the oven: 15.8%;
- Cutting, transport, loading-unloading, closing-opening operations: 5.5%.

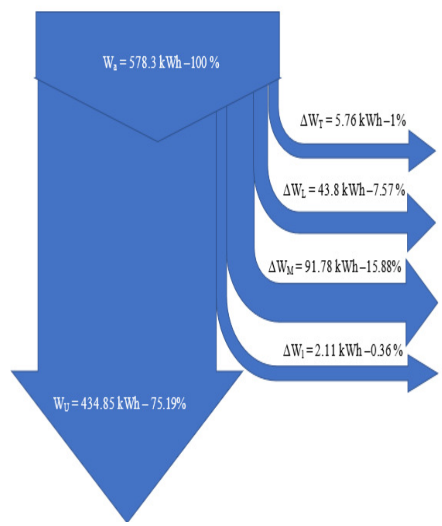


Fig. 9 - Sankey diagram of real EEB, schedule, for PBF [average load]

4.2. Annual real CEB to PBF

Based on the registered energy consumption, of the realized production, admitting the weight of the CEB components, determined within the detailed evaluations, the CEB components can be determined at the level of one year. We present, in this framework, the results obtained at the PBF level, with all the related processes, installations and equipment, for 2018. When performing the evaluations, the hypotheses were admitted:

- The two MLs have the same level of energy performance;
- The components of the CEB retain their share identified in the detailed TEB and EEB;
- Fuel consuming (DF) machines and equipment have an average efficiency of ($\eta_{DF} = 0.35$).

The obtained results are summarized in fig. 10.

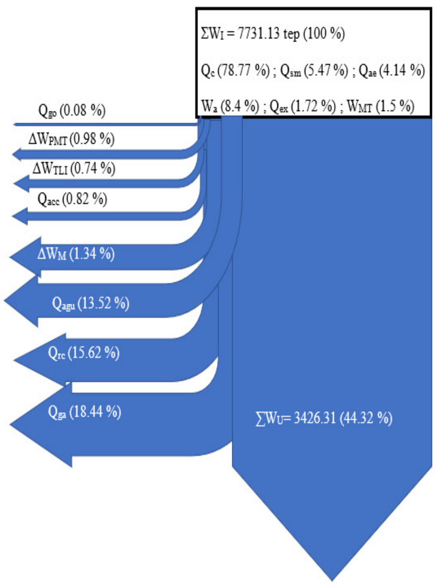


Fig. 10 - Sankey diagram of the real, annual CEB of the PBF [year 2018]

5. ENERGY PERFORMANCE OF THE PBF ANALYZED

5.1. PBF energy performance indicators

It is calculated by applying the ratios given in section 2.4, based on the results obtained for the EBcomponents.The results obtained are presented in Table 8.

Table 8 – EPI values for PBF

Level of evaluation / Indicator	TO (OML)	TO + TD (of OML)	LML (OML)	PBF (for the two ML, for 2018)
Net energy efficency [%]	15.5	48.5	50.75	44.32
Specific energy consumption [toe/t]	0.028	0.034	0.037	0.044
Share of EE consumption in total consumption [%]	-	-	8.14	8.4
Energy intensity [toe/€]	$0.734 \cdot 10^{-3}$	$0.898 \cdot 10^{-3}$	$0.974 \cdot 10^{-3}$	$1.162 \cdot 10^{-3}$
Energy productivity [thousands €/toe]	1.36	1.11	1.03	0.86

5.2. Energy-technological behavior

The measurements and evaluations performed within the CEB of the PBF allow the formulation of the following defining findings in terms of the impact of the BMP on energy flow:

a) The analyzed PBF is efficient in terms of energy, having, in 2018, a specific energy consumption with a value of 1.64 GJ / ton. This value is located towards the lower limit of the specific consumption for PBF registered in Europe and recommended as BPT, where the value of this indicator is in the range [1.5 ÷ 3] GJ/t [1].

b)PBF registered a slight increase in specific energy consumption during the last 3 years, respectively: 1.49 GJ / ton (2016), 1.58 GJ / ton (2017) and 1.64 GJ / ton (2018).

The specific consumption recorded for the period in which the measurements were performed for the detailed CEB, the time interval in which the old manufacturing line (OML) operated, was 1.55GJ/t - between the value in 2016 (1.49GJ / t) and the value in 2017 (1.58GJ / t).

This finding makes it very likely that the new ML has a lower energy performance compared to the OML.

Also, from the emissions analysis bulletin, it is found that the value of the excess air coefficient is much higher ($\lambda = \{7.78; 9.13\}$) than the recommended values ($\lambda = 3$) for such installations [13, 24]. This value, too high, reflects the fact that the process of burning MG in TO is incomplete. From these findings, derives the first measure we recommend (Table 9).

c) The energy losses through the flue gases discharged to the TO and TD chimneys is 29.22% of the energy entered in the contour, which - for the level of energy consumption in 2018 - means 2003.24 toe –year, important amount of energy. The temperature of the two energy fluids is, however, low (112 °C and 110 °C - at TO, respectively 38 °C - at TD), values at which there are currently no economically efficient heat recuperators / savers [25, 26, 27].

d) Analyzing the results obtained within the EIB, the following conclusions can be drawn:

- During the measurements, only the old ML was in operation, but the two transformers (2x1250 kVA) were kept in operation. The recordings made on the transformers show:
  - ➢ The load is distributed evenly on the two transformers (TR);
  - ➢ The load factor of TR is: $\beta_{min} = 0.136$; $\beta_{med} = 0.254$; $\beta_{max} = 0.336$. The optimal value of the loading factor for TR in the PT of the PBF is $\beta_{opt} = 0.587$. It turns out that, while operating with a single ML is more energy efficient, to operate with a single transformer.
- From the load curves, registered on the two TRs, we find a significant consumption of reactive power, respectively: 104.8 kVAr - at minimum load; 266 kVAr - at medium load and 349.7 kVAr - at maximum load. In each case, the power factor is below neutral. It is recommended to keep the reactive power consumption up to the value where $\cos\varphi = 0.92$ (neutral value), by properly adjusting the automatic reactive power

compensator (AQC) and, most likely, supplementing the capacitor banks in the AQC.

• With reference to the EE quality, in the analyzed contour, the following are found:

- The effective value of the voltage is normal and balanced on the three phases;
- The content of voltage harmonics at the level of the transformer station (TR1, TR2) falls within the norms. In the case of current, there is a slight overrun, in relation to the recommendations: THDI = [10.9 ÷ 23]%. Too high values of the THD_I indicator, at the PT level, are determined by the propagation of current harmonics at the level of large receivers (motors), powered by converters:

•Press: $THD_I \in [38.2 \div 117.4]\%$;
•Flue gas fan: $THD_I = [94.1 \div 112.4]\%$;
•Fan for hot air transfer from TO, to TD: $THD_I \in [112.3 \div 143.3]\%$;

Most likely, the cause of the propagation of the deforming residue from the equipment that generates it (the converters through which the mentioned motors are supplied) is the non-dimensioning or the non-functioning of the “network filters” that must equip the converters.

• Electric lighting is provided, for the most part, with efficient lamps (LEDs).

5.3. Resources for increasing energy efficiency

The synthesis of the measures for increasing the energy efficiency is presented in table 9, and their reflection in the optimized CEB is highlighted in fig. 11.

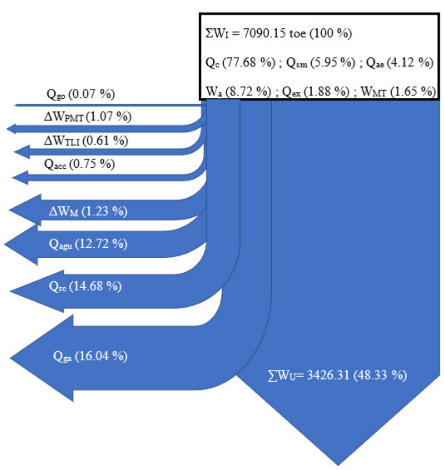


Fig. 11 - Sankey diagram of the CEB optimized, annually, of the PBF

The annual EPI values for the optimized CEB will be:

• Net energy efficiency: $\boldsymbol{\eta_{no} = 18.33[\%]}$
• Specific energy consumption: $\mathbf{c_{no} = 0.04[toe/t]}$
• The share of EE consumption in the total energy consumption: $\mathbf{p_{EO}} = 8.72\mathbf{[\%]}$
• Energy intensity: $\mathbf{I_{wo} = 1.07\ x10^{-3}[toe/€]}$
• Energy productivity: $\mathbf{p_{wo} = 0.94\ [€/toe]}$

Table 9 - Proposed measures to improve energy efficiency at the PBF

No.	Proposed measure	Estimated energy savings [toe/year]	Investment required [thousand Euro]	Investment payback time [years]
1.	Evaluation, maintenance and adjustment actions on the main equipment in the new ML structure, and checking the burns at the OML, in order to increase their energy performance. Implementation, for this purpose, at PBF level, of a continuous monitoring and evaluation system, in terms of energy.	627	60	0.5
2.	Equipping PT with an automated switching equipment of one of the transformers, depending on the load level	0.2	1.4	7
3.	Distributed compensation (for large motors) of reactive power (2x 260 kVAr)	11.1	1.5	0.5
4.	Replacement or maintenance of "mains filters" in converters supplying 3 electric motors	2	17.7	9
5.	Replacement of less efficient lamps (LVM, TF) with LED light sources	0.63	4.3	7

All 5 measures are technically and economically feasible.

As mentioned in [23], an applicable way to improve the energy performance of industrial consumers is to identify the optimal level of production by applying the criterion "minimum specific energy consumption" [21].

In this case, based on the data in tables 3 and 7, the energy characteristics of the BMP were identified, with reference to the two energy agents [EE and MG], namely:

$W_{MG} = f\ (V_{FP})$; $C_{nMG} = f\ (V_{FP})$ – for MG;
$W_{EE} = f\ (V_{FP})$; $C_{nEE} = f\ (V_{FP})$ – for EE;
$W_S = f\ (V_{FP})$; $C_{nw} = f\ (V_{FP})$ – for MG+EE

Table 10 - Elements for optimizing specific consumption

Month	V_{FP} [thousands of tons]	W_{EE} [GWh]	W_{GM} [GWh]	W_S [GWh]
1	0	0.014	0.003	0.017
2	3.84	0.27	2.32	2.59
3	11.84	0.63	5.83	6.46
4	16.47	0.67	6.81	7.48
5	18.32	0.73	7.41	6.14
6	17.3	0.74	6.6	7.34
7	19.4	0.76	7.12	7.88
8	21.08	0.79	7.87	8.66
9	19.56	0.79	7.56	8.35
10	20.61	0.89	8.32	9.21
11	19.55	0.89	8.19	9.08
12	6.82	0.37	3.1	3.68

In accordance with the recommendations of the literature [28, 29], three models were tested:

Linear: $W = a \cdot V_{FP} + b$ (26)

Parabolic: $W = a \cdot V^2_{FP} + b \cdot V_{FP} + c$ (27)

Logarithmically: $W = a \cdot \ln V_{FP} + b$ (28)

$W = \{W_{MG}, W_{EE}, W_S\}$

In each case the 3 specific consumptions were expressed $[C_{nGM}, C_{nEE}, C_{nw}]$ as W/V_{FP} and the accuracy of the estimation was determined, by calculating the indicator:

$$r=\frac{\sum_{i=1}^{12}(Wi-Wmed)^2-\sum_{i=1}^{12}(Wi-\widehat{W}i)^2}{\sum_{i=1}^{12}(Wi-Wmed)^2} \quad (29)$$

where:
W_i - monthly, real consumption (observed);
W_{med} - average (monthly) value of consumption;
$\widehat{W}_i$ - adjusted monthly consumption (given by the regression equation).
The better the estimation, the better the r is closer to 1 [28].Table 11 shows the results obtained.

Table 11 - Equations of energy characteristics of the analyzed BMP

Model / Energy agent	Linear	Parabolic	Logarithmically
EE	$W_{EE}=0.0366 \cdot V_{FP}+0.0954$ $C_{nEE}=0.0366+\frac{0.0954}{V_{FP}}$ r = 0.9537	$W_{EE}=0.00075 \cdot V_{FP}^2+0.0225 \cdot V_{FP}+0.0966$ $C_{nEE}=0.00075 \cdot V_{FP}+0.0225+\frac{0.0966}{V_{FP}}$ r = 0.9133	$W_{EE}=0.3477 \cdot \ln V_{FP}-0.241$ $C_{nEE}=\frac{0.3477 \cdot \ln V_{FP}}{V_{FP}}-\frac{0.241}{V_{FP}}$ r = 0.928
MG	$W_{MG}=0.3646 \cdot V_{FP}+0.6166$ $C_{nMG}=0.3646+\frac{0.6166}{V_{FP}}$ r = 0.972	$W_{MG}=-0.009 \cdot V_{FP}^2+0.567 \cdot V_{FP}+0.007$ $C_{nMG}=-0.009 \cdot V_{FP}+0.567+\frac{0.007}{V_{FP}}$ r = 0.9823	$W_{MG}=0.3554 \cdot \ln V_{FP}-2.996$ $C_{nMG}=\frac{0.3554 \cdot \ln V_{FP}}{V_{FP}}-\frac{2.996}{V_{FP}}$ r = 0.950
MG + EE	$W_S=0.3853 \cdot V_{FP}+0.7956$ $C_{nW}=0.3853+\frac{0.7956}{V_{FP}}$ r = 0.933	$W_S=-0.0076 \cdot V_{FP}^2+0.56 \cdot V_{FP}+0.2076$ $C_{nW}=-0.0076 \cdot V_{FP}+0.56+\frac{0.2076}{V_{FP}}$ r = 0.9433	$W_S=3.6866 \cdot \ln V_{FP}-2.826$ $C_{nW}=\frac{3.6866 \cdot \ln V_{FP}}{V_{FP}}-\frac{2.826}{V_{FP}}$ r = 0.879

We find that, in case of MG and MG+EE, the parabolic model is the most appropriate and in EE case the linear model is most suitable. To identify the optimal value of production we will use the parabolic model and we solve the equations:

$$\frac{dC_{nEE}}{dV_{FP}}=0.00075-\frac{0.0966}{V_{FP}^2}=0 \quad (30)$$

$$\frac{dC_{nMG}}{dV_{FP}}=0.009-\frac{0.007}{V_{FP}^2}=0 \quad (31)$$

$$\frac{dC_{nW}}{dV_{FP}}=0.0076-\frac{0.2076}{V_{FP}^2}=0 \quad (32)$$

We get:

for EE: $V_{FPopt}=\sqrt{\frac{0.0096}{0.00075}}=\sqrt{12.8}=3.578$ thousand tons

for MG: $V_{FPopt}=\sqrt{\frac{0.007}{0.009}}=\sqrt{0.778}=0.882$ thousand tons

for the sum W (EE and MG):

$V_{FPopt}=\sqrt{\frac{0.2076}{0.0076}}=\sqrt{27.316}=5.226$ thousand tons

The 3 values are unrealistic, given the real production capacity of an ML of PBF (table 10). Therefore, in this case, we will identify the optimal value of production as that value at which C_{nW}, calculated with the relation from table 11, for the cumulated energy consumption (MG + EE), has the minimum value.
Figure 12 represents the energy characteristics of the analyzed BMP for the sum of EE and GM.

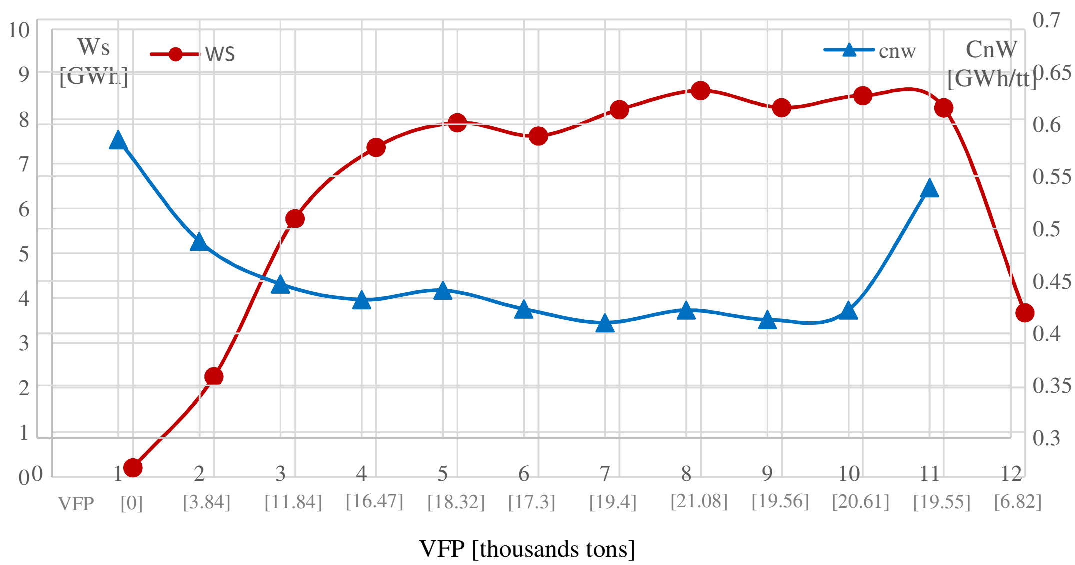


Fig. 12 – Energetic characteristics of the analyzed BMP

6. CONCLUSIONS

The ceramic industry consumes a significant amount of energy, mainly for the process of burning the brick. Within the analyzed BMP, the EE required for the drying and burning processes of the brick is produced by the combustion of MG and represents almost 88% of the total energy consumption.

The records show that the main phases in which EE is consumed are: management of ventilation for the dryer (31.5%), crushing + laminating + shaping (24.7%) and pre-processing (16.3%).

The energy efficiency of the processes is relatively good (44.32%) - at the average annual load, for processes of this type in which ET is obtained by burning MG. The relatively high energy performance of the analyzed BMP is also confirmed by the level of specific energy consumption, located towards the lower limit recorded in similar processes. The analyzed processes lend themselves to improvements in terms of energy performance, by applying energy efficiency measures that are feasible from a technical and economic point of view and that can lead to an increase of about 4% in net energy efficiency.

Improving the energy performance of BMP can also be achieved by optimizing the load level, by applying the criterion "minimum specific energy consumption". The parabolic model offers the best approximation of the energy characteristic for the analyzed BMP, but the realistic value is obtained for the cumulated energy consumption (EE + MG).

Applying this model, the value of the optimal load is obtained (21,080 tons), at which the specific consumption is 410 kWh/ton.

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