Energy Study of Manufacturing Processes in the Natural Stone Industry

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Abstract

For the last few decades, an ecological consciousness has been developed due to the increase, not only of the energy consumption, but also of the price of fossil fuels. The present work aims to characterize the energy consumption in the transformative area of the natural stone sector to find energy saving measures.

In the first part of the present dissertation a study is developed to find the optimal operating parameters of a stone cutting machine. Going through a test procedure, where the energy consumption of the machine and the wear of the utilized tool were recorded, it was possible to achieve overall savings of about 15%.

In the second half of the present thesis a case study is carried out in a typical natural stone processing factory. In this study it is identified that the production process is responsible for approximately 50% of the total primary energy consumption of the company and, therefore, it will be the focus of this part of the work. By conducting an energy audit on the plant's main production line, it was possible to identify four energy efficiency measures, without any associated investments. These measures, if applied, would result in a primary energy savings of around 20.7 toe (tons of oil equivalent), corresponding to 5.1% of the total consumption, and economic savings of 21 910 €, about 10.2% of the annual energy related costs.

Keywords: Energy Efficiency, Energy Savings, Operating Parameters, Production Process.

1. Introduction

Portugal is a country with a lack on fossil resources, such as oil, coal and natural gas, which are responsible for satisfying the country's energy needs, resulting in a high external energy dependence (74,8 % in 2016). This situation leads to a constant necessity to increase the contribution of renewable energy sources and therefore reducing the consumption of these fossil fuels at a national level [1]. Although the value of energy dependence in Portugal has decreased in the past few years, it is largely above the European average (53,6 %) [2].

The mentioned decrease over the last decade is mainly due to the growth in domestic production based on renewable energies, which nowadays represent a large part of the production in Portugal. In the first quarter of 2018, this production reached 62.1% (9,382 GWh), as can be seen in the figure below.

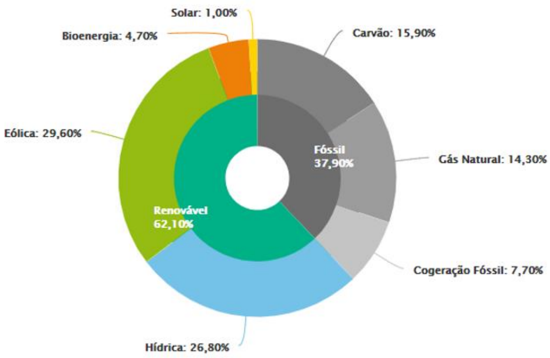

Figure 1 - Electricity Production in Portugal, first quarter 2018 [3]

Due to the large increase in global energy consumption over the last decades and a huge use of non-renewable resources to satisfy this consumption, protocols to control the world energy production began to emerge.

The European Commission, in order to increase energy efficiency and reduce GHG emissions in the EU, establishes the 20-20-20 initiative. This initiative has three main goals to be completed by the year 2020. They are: reducing GHG emissions by 20%, achieving a consumption from renewable sources of at least 20%, and finally energy efficiency must increase 20%, all comparing to the year of 1990 [4].

Apart from this, in Portugal, the National Energy Strategy (ENE 2020) was adopted, not only to achieve the objectives described above, but also to reduce the energy dependence. This strategy intend to reach a financial growth and a decrease in energy dependence, by a greater focus on renewable energy, an increase in energy efficiency and a growth in economic and environmental sustainability [5].

2. Literature Review

This chapter will be divided in two sections, the first one to explain the main production processes in the natural stone industry and the second to explain the material removal mechanism on natural stone.

A. Main Production Processes

The present dissertation, as mentioned above, is related to the natural stone sector. This sector is divided in two distinct phases, the extraction and the transformation. The extraction, carried out in quarries distributed all over the world, aims to obtain blocks of stone. From this stage on the transformation phase of the natural stone begins. At this point those blocks will be processed in order to obtain semi-finished or finished products. The main processing steps are the sawing of the blocks to obtain slabs, the surface treatment and then the cutting of these slabs to obtain products with the desired dimensions, resulting in the final product. The presence of water is a constant in all productive processes in natural stone industry, guaranteeing cleanliness and cooling. [6], [7].

It is important to note that in this sector, the raw material is often divided into two major classes: granite and marble. This division is made based on the hardness of these two stones and therefore the ease of processing, the granite being a hard stone and the marble a soft stone.

A.1. Single Blade and Single Wire Equipment

These machines are not only suitable for square irregular blocks but can also be used in the sawing of slabs with different thicknesses from the normal production of a factory.

These machines have two different processing technologies, one uses a diamond blade as a tool and the other a diamond wire. The general mode of operation is identical in both, having an electric motor that inputs movement into the tool and another that is responsible for the descendant movement of the structure. The second electric motor is the responsible for the processing throughput.

The single wire allows a significantly faster processing and lower energy costs, when compared to the single blade equipment. The single wire also differs from single blade because it is suitable for processing both marble and granite, while single blade is appropriated only for marble.

A.2. Multi Blade and Multi Wire Equipment

These machines are used for sawing blocks of stone to obtain slabs. Since they are equipped with several blades or wires, the productivity of these machines is clearly superior to that of previous equipment, when they were in charge of sawing slabs.

The operation mode of these machines is very similar to that described previously, but there is an increase in the number of tools (blades or wires). This difference necessarily implies more powerful electric motors and stronger structures to support the tougher interaction between tools and material.

As seen before, there are important differences between these two devices. Diamond wire technology has always a higher productivity and a lower energy costs when compared to blade technology.

Figure 2 and Figure 3 illustrate the equipment described so far.

Figure 2 - Examples of single blade and single wire machines, respectively

Figure 3 - Example of multi blades and multi wire machines, respectively

A.3. Polishing Machines

The stone slabs obtained from the processes described above are, in most cases, subjected to surface treatments in the polishing machines.

These machines have several polishing heads supported by a cross bar that moves perpendicularly to the movement of the slabs. The stone, transported by a conveyor belt, runs through the entire polishing machine, where its rotating heads, making pendulous movements, contact the slab surface.

A.4. Bridge Cutting Machines

This type of equipment is extremely used in the processing stage of the natural stone industry thanks to its enormous versatility of work. Most companies involved in the transformation of natural stone have on their facilities bridge cutting machines for slabs cutting. The cut is performed using disk tools with several diamond segments on its perimeter.

B. Abrasive Process

In the natural stone processing the material removal is achieved through abrasive processes. The used tools usually contain, as mentioned before, diamond segments. These segments have diamond grains, distributed randomly in a metal matrix, which will be responsible for the abrasion of the material to be removed.

B.1. Abrasive Wear

Abrasive wear is caused by the in-motion interaction of a hard particle and the softer surface of a body. In other types of wear (adhesive wear, tribo-chemical and surface fatigue), disintegration of particles from the surface of a body can occur, which causes these particles to be stuck between the surfaces of two bodies, causing wear. This wear is referred as three-body abrasive wear. The three-body wear can also be obtained by the deliberate addition of an abrasive sludge to act as abrasive particles.

Very often, in material removal processes, such as cutting, thinning and machining, cutting segments are used. These segments are formed by a matrix and by particles, usually diamond, which are fixed in the matrix structure. In this material-tool interaction, those particles will cause wear in the adjacent body, so it is a two-body abrasive wear [8]–[10].

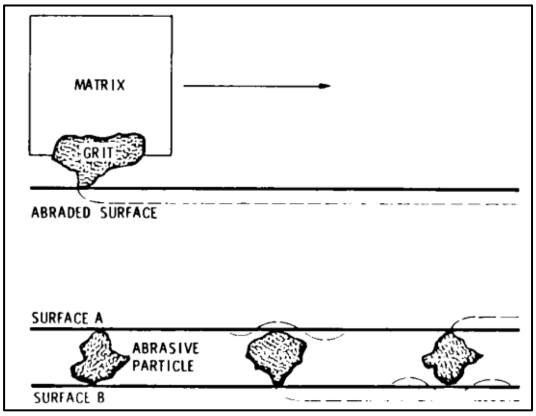

Figure 4 – two and three-body abrasive wear, respectively [11]

B.2. Abrasive Contact

In order to understand the interaction between a disk tool and the material in a cutting process, it is important to study the kinematics and dynamics of the abrasive contact between them. Doing that, it will be possible to identify the main parameters that influence the physics of this type of process.

Through the kinematic analysis of the process it is possible to define parameters such as the material removal rate, the penetration of the abrasive particles in the material to be cut and, consequently, aspects related to the theoretical chip resulting from this interaction. The parameters that are possible to control in this configuration are the peripheral speed of the tool (v_s), the feed speed (v_w) and the depth of cut (a_p). The material removal rate is given by:

$$Q_w = a_p \cdot b_w \cdot v_w \qquad (1)$$

where b_w is the thickness of the cutting segments. The equivalent chip thickness, commonly used in experimental works instead of the theoretical value, is given by:

$$h_{eq} = a_p \frac{v_w}{v_s} \qquad (2)$$

To complete the theoretical analysis of cutting, using a circular tool, it is important to approach the dynamics of the process. Depending on the material, tool and operating parameters selected, there will be resulting strength, power and energy.

The resulting force of the contact between the cutting tool and the material to be cut can be divided in two main components, the tangential force, F_t, and the normal force, F_n.

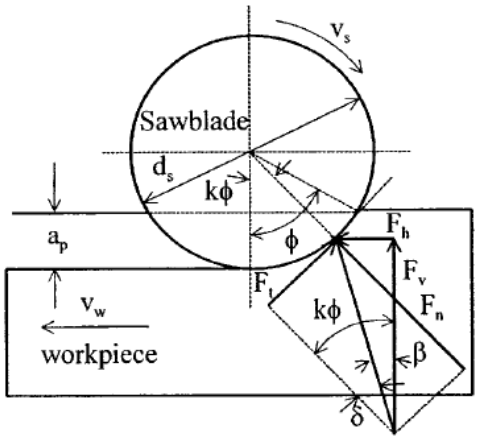

Figure 5 - Forces present in the cutting process with a circular tool

The tangential force, usually much smaller than the normal force, is directly related to the power, P, involved in the process as follows:

$$F_t = \frac{P}{v_s} \tag{3}$$

Finally, it is relevant to define a parameter that relates the power and the material removal rate. It is called specific energy, u, and represents the energy consumed per unit of removed volume [12]–[14].

$$u = \frac{P}{Q_w} = \frac{F_t \cdot v_s}{a_p \cdot b_w \cdot v_w} \tag{4}$$

3. Experiments on Tool Wear versus Energy Consumption

The experiments were performed on a bridge cutting machine, where a typical granite disk, with 24 diamond segments, was used. During the test, six slabs of granite (Rosa Porrinho) were cut, and the information concerning energy consumption, wear of the tool and resulting forces were recorded.

In order to understand the behaviour of the cutting machine in action, some preliminary tests were performed. These were intended to illustrate the variations of the machine's power consumption, while some operating parameters were changed. Using a combination of 3 values of feed speed with 3 values of peripheral speed of the tool and 3 values of depth of cut were made different cuts. Analysing the results, it was possible to conclude that there were cuts that theoretically were more severe (by comparison of the h_{eq} parameter) but presented lower power consumption. With this in mind and ensuring that the values of depth of cut and feed speed were not changed, since they are directly related to productivity, the official tests were performed.

As mentioned above, six stone slabs were processed here, three of them were cut with a rotational speed of 1430 rpm and the remainder at a rotational speed of 1100 rpm. The tool segments were measured using a laser sensor, and the tool wear was obtained by the difference of the measurements at the beginning and at the end of each processed slab. The table bellow has the relevant information about the operating parameters of the tests carried out.

Table 1 - Operating parameters used

Rot. Speed rpm	Feed speed [mm/s]	Depth of cut [mm]	Water flow [l/min]
1430	30	18	26
1100			

3.1. Results

After completing the tests for both rotational speeds, the important results are presented below.

A. Tool Wear

For the calculations and results obtained here it was used, to compute the data from the laser sensor, a program developed in MATLAB® for the total analysis of the tool. Choosing to analyse the tool as a whole, instead of just a cutting segment, is beneficial as it guarantees the minimization of the measurement error, since the sampling is enlarged, and also allows to ensure a coverage of all the segments involved in the cut.

The following chart caries all the information regarding the tool wear as a function of the cut area.

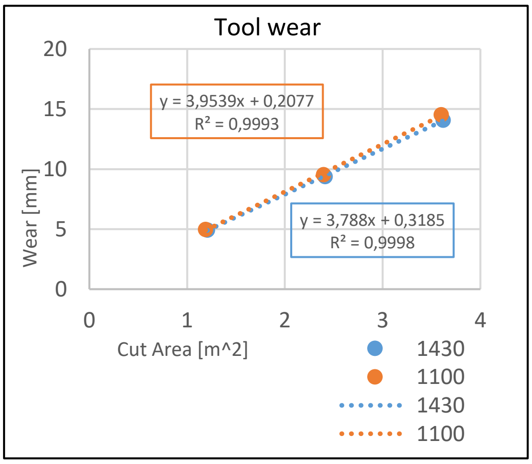

Figure 6 - Tool wear for both rotational speeds

Using the linear equations present above, it is possible to obtain the average tool wear per square meter cut for each velocity, which when compared results in an insignificant difference of 1,34%.

Analysing the resulting forces, which are directly related to the severity of the cut [13], it is possible to conclude why the variation has been so small.

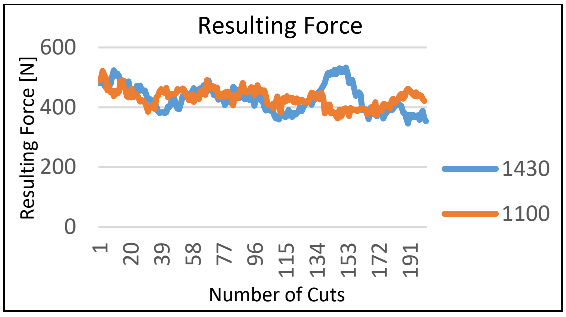

Figure 7 - Resulting forces on the tool for both rotational velocities

As can be seen in the chart above, the forces are very coincident for the tested speeds, they even come to cross each other. Therefore, it is possible to affirm that for the studied speeds the variation of the tool wear can be neglected.

B. Energy Consumption

Once concluded that the tool wear is not a determining factor for the general savings of the process, in this specific test, it remains to analyse the data related to the energy consumption. It is possible to affirm that this will be the main factor influencing the savings resulting from the variation of the operating parameters.

In the power absorption chart below, the interceptions present in Figure 7 are no longer observed. In this one the lines are clearly separated and a reaction to the variation of the rotational speed is clear.

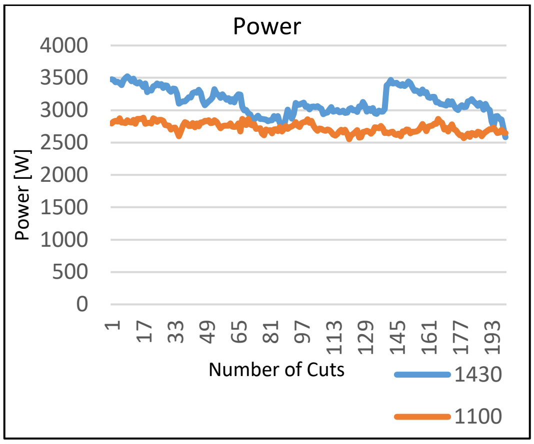

Figure 8 - Power profile of both velocities studied

Computing the energy consumption data, once again per square meter cut, it was obtained that from a variation of the rotational speed from 1430 to 1100 rpm results a variation of about 15,16%, from which it is concluded that it is possible to achieve not only energy but global savings.

4. Case Study: Mármores Galrão

To complete the present dissertation, it is carried out a case study where a typical natural stone processing plant is analysed. In this analysis the production process of the company Mármores Galrão was the focus since it is responsible for about 50% of the company's total energy consumption (408,5 toe on 2017).

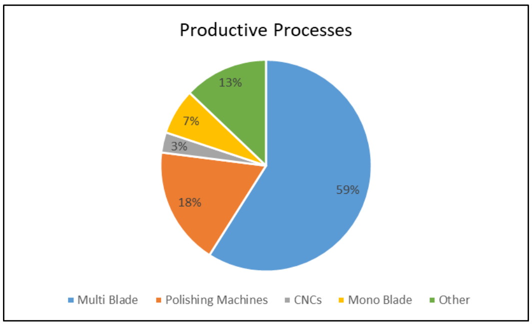

Figure 9 - Productive processes energy consumption weight

The processes that were originally considered to be the most energy-intensive ones and those that were part of the main production line, in the next figure, of the plant were considered. The equipment responsible for these production processes were submitted to energy audits. The goal was to measure those processing exactly the same type of natural stone to make a feasible comparison.

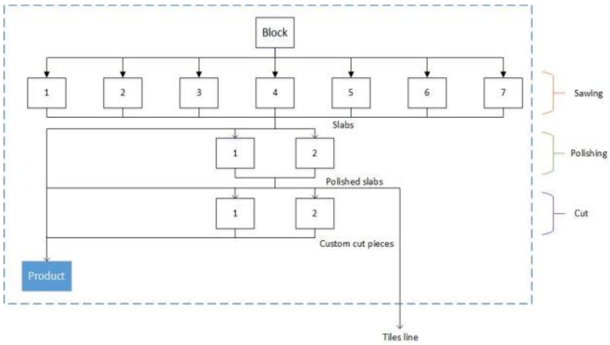

Figure 10 – Main production line

The main production line of the plant is composed by 7 multi blade machines, responsible for sawing the blocks, 2 polishing machines, to apply a surface treatment on the slabs, and 2 CNC cutting machines to obtain custom cut pieces. All these equipment, excluding the multi blade machines number 1 and 5, were measured using a power analyser while they were processing the same type of marble. These audits allowed, not only to identify that the multi blade machine 2 needs and intervention as it is consuming almost twice as the rest (Figure 11), but also to identify the most attractive production route.

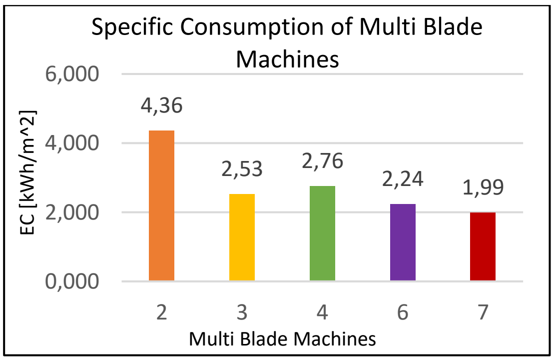

Figure 11 - Specific consumption of multi blade machines

A. Energy Saving Measures

At this point, the main energy saving measures found in Mármores Galrão plant will be presented. The savings resulting from such changes, both in the form of primary energy and in euros, will be calculated.

Note: At this point, whenever the economic savings achieved are approached, the value of 0,1126 €/kWh, obtained directly from the electricity bills, will be used, which also includes the costs associated with power and fixed terms. Except in the case of section 4.2.2. where is performed a detailed calculation to obtain the price difference for each period of the day. In the case of primary energy, the conversion factor of 0,215 kgep / kWh is used.

A.1. Optimal Production Route

The optimal production route, studied at this point, refers only to the main production line. That said, this calculation concerns the 7 multi blade machines, the 2 polishing machines and the 2 CNC cutting machines measured.

Regarding the multi blade machines, the best option is to process stone using the machine number 7. Nonetheless, it has been shown that the machine 2 was consuming almost twice as the remaining, so the possible savings are obtained when the annual consumption of this machine is compared with the remaining's average. Resulting a value of 12,29 toe of primary energy saved and about 6438 €.

In the case of the polishing machines, only two are available, so the optimal production route in this step is defined by the one with the lowest energy consumption. Through the disaggregation of the energy consumption present in Figure 9 and knowing that the productive processes are responsible for half of the total consumption, it is possible to reach an annual consumption for these equipment of 36,77 toe. From this value it was verified that the polishing machine 1 is responsible for 19,74 toe (54%) and polishing machine 2 for 17,02 toe (46%). Once again, regarding the annual savings when manufacturing in machine 2 instead of using the former, values of 2,72 toe and 1425 € are obtained.

From the CNC cutting machines audit it was possible to obtain that the savings between processing in CNC 1 or CNC 2 is about 3,1%. This is an insignificant difference, indicating that these two devices have a very similar behaviour when they are processing under the same conditions. For the annual savings, as expected, it is almost negligible, reaching values of 0,1 toe for primary energy, and 52 € when processing in CNC 1 cutting machine instead of CNC 2.

It is now possible to account the annual savings by stop processing in the largest energy consuming equipment and to process in those with the lowest consumption. In the case of the multi blade machines the option is to stop processing in multi blade 2, as explained above. This savings allows a reduction of primary energy consumption by 15,09 toe, which corresponds to about 7915 €.

A.2. Multi Blade Processing Planning

It will now be analysed the multi blade processing planning as far as the processing hours are concerned. For this, it is important to note that in this case electric energy is charged based on a quarter-hour rate (peak, full, off-peak and super off-peak).

To calculate the optimal processing starting hour it was considered that sawing a block in these multi blade machines take, in average, 14 hours. The adjustment of the processing was carried out to take advantage of all periods of super off-peak and off-peak tariffs, avoiding peak periods, but always without compromising the productivity of the line. As the schedules corresponding to each tariff, and even the tariffs, varies from daylight saving time to winter time, different solutions were obtained for both situations.

For daylight saving time the optimal solution is to start the sawing process at 5:00 p.m., avoiding the peak tariff, taking full advantage of the off-peak and super off-peak tariffs. When this measure is implemented it is possible to achieve savings of 7054 €, only in the summer period. In the case of winter time, it was not possible to completely avoid the peak tariff since this would require a stop in the production process, which is not advisable. Starting the process at 9:00 p.m. was the best solution found for this period, being possible to achieve savings of about 3994 €. Joining both periods mentioned above together, results a reduction of 21% of the total energy costs of these machines which corresponds to an economic saving of 11048 €.

A.3. Optimization of Polishing Machines Control System

Throughout the audit of these machines, it was found that there were fans and drying rollers, at the end of their conveyor belt, which were often not processing any stone slab. Immediately after one of the polishing machines is an equipment capable of recording the dimensions of the polished slab, as well as the time it passes through. Using this information, within a period of 5 normal days of production, it was possible to conclude that, on average, these equipment were not processing during 73.85% of the time. The possibility of changing the control of these equipment was studied so that, when there are no slabs passing in its zone of operation, they are turned off. It is therefore possible to achieve with this measure savings of about 4,3 toe, corresponding to 2265 €.

A.4. Extrapolation of the Tool Wear versus Energy Consumption Experiments

In the third chapter, a methodology of tests that could provide energy savings to the cutting process was approached. Taking this into consideration and knowing that the company studied is quite large, there are several machines where these savings could be achieved. In addition to the previously presented CNC machines 1 and 2, there are two other cutting machines which, although they have not been analysed, their annual consumption is known. All the referred cutting machines have the same processing principle as the equipment used for the Chapter 3 tests, which is why it is plausible to consider general savings of around 15%. Considering that and knowing that the total consumption of these four cutting machines is about 8,68 toe, annual energy savings of 1,3 toe is obtained, which corresponds to approximately 682 €.

5. Conclusions

As a result of the study carried out in the first half of this abstract it can be concluded that it is possible to achieve energy savings by improving the operational parameters of the process. It should be noted that the tool wear is a parameter to consider, ensuring that energy savings are not compromised by the increase of that. Although the optimum operating parameters were not reached due to lack of resources and time, total savings of 15% was achieved. This value becomes significant, considering that it is a technology used by the great majority of companies dedicated to natural stone transformation.

In the second half of the abstract, the processing equipment of the company were analysed by an energy audit. This study allowed the comparison of the different equipment dedicated to the same type of process, from where it was readily possible to define an optimal production route. In addition to this, three other measures of energy efficiency were also found, the first one is applied to the blocks processing on the multi blade machines, the second is directly applied to the polishing machines and the last one focused on the cutting machines. The following table reviews the measures found, as well as the annual benefits that come from them.

Table 2 - Energy saving measures review

Measure	Savings [€]	%	Savings [toe]	CO2 Reduction
Optimal Production Route	7915	3,7	15,1	33
Multi Blade Processing Planning	11048	5,2	-	-
Optimization of Polishing Machines Control System	2265	1,1	4,3	9,4
Extrapolation of the Tool Wear versus Energy Consumption Experiments	682	0,3	1,3	2,8

This measures lead to savings of about 20,7 toe, corresponding to a 5,1% reduction in primary energy consumption, and an economic saving of around 21910 €, representing a 10,2% saving in factory's electricity bill.

6. References

[1] DGEG, "BALANÇO ENERGÉTICO 2016-Sintético," pp. 1–7, 2016.

[2] EUROSTAT, "refreshTableAction @ ec.europa.eu." [Online]. Available: http://ec.europa.eu/eurostat/tgm/refreshTableAction.do?tab=table&plugin=1&pcode=tsdpc240&language=en.

[3] APREN, "APREN - Produção." [Online]. Available: http://www.apren.pt/pt/energias-renovaveis/producao.

[4] "2020 climate & energy package - Climate Action - European Commission." [Online]. Available: https://ec.europa.eu/clima/policies/strategies/2020_en.

[5] L. C. Freitas *et al.*, "Presidência do conselho de ministros," in *Dr*, 2004, vol. 1, pp. 1–16.

[6] I. Paspaliaris, *Machines and tools for stone quarrying and processing*. Athens: Laboratory of metallurgy National technical University of Athens, 2003.

[7] I. Paspaliaris, *Complementary technologies for stone processing*. Athens: Laboratory of metallurgy National technical University of Athens, 2004.

[8] I. M. Hutchings and P. Shipway, *Tribology : friction and wear of engineering materials*. .

[9] H. P. Jost, "Tribology - Origin and future," *Wear*, vol. 136, no. 1, pp. 1–17, 1990.

[10] K.-H. Zum Gahr, *Microstructure and wear of materials*. Elsevier, 1987.

[11] D. H. Buckley, *Surface effects in adhesion, friction, wear and lubrication*, vol. 85, no. 2. 1983.

[12] W. B. Rowe and B. Dimitrov, *TRIBOLOGY OF ABRASIVE*. .

[13] X. Xu, Y. Li, and S. Malkin, "Forces and Energy in Circular Sawing and Grinding of Granite," *J. Manuf. Sci. Eng.*, vol. 123, no. 1, pp. 13–22, 2001.

[14] S. Turchetta, "Cutting force in stone machining by diamond disk," *Adv. Mater. Sci. Eng.*, vol. 2010, 2010.