Strategies for energetic efficiency in a tobacco industrial unit

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Abstract

In the past years there has been a rising concern about the use of energies and their sustainability, being of great importance that the systems used in the different industries have their energetic efficiency maximized in order to avoid unnecessary wastes and emissions. All this should be done, of course, without compromising the production levels. Measures such as implementation of renewable energies and rational use of energy should always be considered.

The goal of the present paper is to evaluate the energetic situation of the industrial unit of Philip Morris International, having in sight the implementation of measures that allow savings, both in an economic and environmental way. To do so, audits were performed on the compressed air and steam production systems since this two make over 40% of the consumption of the primary energy of the factory. A study was also conducted to analyze the viability of installing a combined heat and power unit (cogeneration), given there is a great demand for both heat and electricity in the processes.

Results show that the compressed air system was not being efficient and an investment of 190 000 euros can lead to savings of 70 000 € and 165 tons of oil equivalent (toe) per year. Such investment would have a payback period of 3,7 years and represents a 13 % improve in this system energetic efficiency. As for the cogeneration, the study performed showed that covering the full thermal power with a Gas Turbine would produce give place to savings of 365 000 € and 1005 toe per year. This would require an investment of 1 370 000 euros, which gives a payback period of 3,6 years and a global 14,4 % energetic efficiency improve.

***Key Words*: Energetic Efficiency, Compressed Air, Cogeneration, Steam System, Primary Energy Savings**

I. Introduction

The rising consumption of primary energy over the last few years gave place to a general concern from the governments for the environment sustainability, CO_2 emissions and the rational use of energy. The trend has been to use renewable forms of energy rather than continuing investing on fossil fuels. Efforts have been made to reduce the ecological footprint all over the world.

In Portugal, the weight of renewable sources in primary energy went from 16 to 23% over the last decade. With this policy, the dependence of energy from exterior suppliers has decreased roughly 10% [1]. By the beginning of the year 2017, more than 50% of the electricity produced in Portugal came from renewable sources of energy, making it the fourth country in Europe with the highest incorporation level of such form of energy [2], [3].

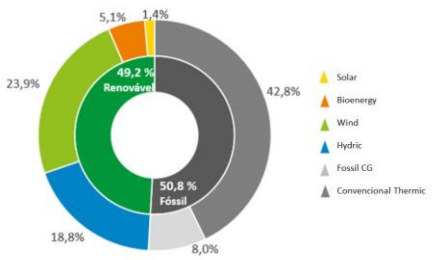

Figure 1 - Production of Electricity by source [2]

Concerning the efforts made at an international level, in March 2007 the European Commission launched the initiative 20-20-20 which had the objective of turning Europe's economy into a low carbon emissions one and contributed to the creation of over a million jobs. The goals of this initiative consisted of a 20% reduction of CO_2 emissions (comparing to the year of 1990), that 20% of the energy comes from renewable energies and an improvement of 20% in energetic efficiency by the year of 2020 [4].

Apart from this, the Portuguese government also applied an internal Energy program, in which states that, among others, cogeneration (CG) systems should be encouraged as it represents one of the most efficient forms of reducing the consumption of primary energy. The European Commission determined that studies should be conducted in every state member to identify the potential of cogeneration. This technology was first used in Portugal in 1940 and has nowadays 2000 installed MW and efficiencies above 80% [5].

II. State of the Art and Methodology

This chapter will be subdivided in two sections, the first one to cover related work about Compressed Air Systems (CAS) and the second about Cogeneration.

A. Compressed Air System

The CAS are responsible for 10% of the total use of electric energy in the industrial sector in Europe. In this kind of systems, the investment cost accounts for about 16%, the maintenance cost 6% and energy costs for the remaining 78% [6].

A CAS is not only made by the compressors but also by the electric motor which is responsible to transmit mechanic power to the shaft, the air treatment systems, distribution network and the control equipment.

There are two types of compressors: Volumetric and Dynamic. In the first type, the compression is achieved by a reduction of the volume. In Dynamic compressors the kinetic energy is used to be transformed in pressure.

In the distribution network, the sizing and material (typically inox steel) of the pipes is a very important factor in order to minimize pressure drop. Turbulence in the air flow should be minimized as well. That can be done by avoiding short radius bows and to privilege the use of “Y” joints instead of “T”. The air reservoir has the function of stabilizing the pressure.

The air treatment unit is of great importance to the global efficiency of the CAS. The air should be as dry, cold and clean as possible to avoid pressure drop and corrosion in the distribution pipes. Several studies have been conducted on this component of the CAS. The location of air filters is an important issue that should be taken in consideration when installing one. Latest technologies are able to remove 99,9999% of the undesired particles of the air. The choice of a correct filter can represent more than 400€ of savings per year [7]. The other part of the treatment unit are the dryers which are divided in two categories: Adsorption and Refrigeration. The choosing of the type depends of the Dew Point of the air being produced. When it is above 2ºC it is recommended to use refrigeration dryers. Below 2ºC absorption dryers are more suited. In the industry, practically all dryers work with the absorption principle. Basically, the air passes through an absorbent material (can be solid or liquid) which as the capability of retaining the water molecules. The equipment is constituted by two towers: one for drying the fluid and the other to regenerate the absorbent molecules. From time to time, the tasks of the tower are swapped (when all the material in tower 2 is regenerated) [8].

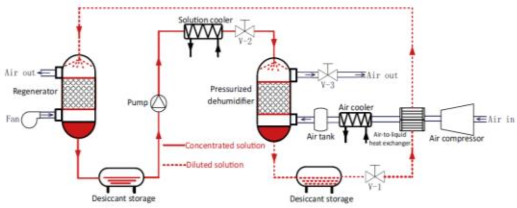

Figure 2 - Drying System Layout [8]

Finally there is the Control System. This system is responsible to choose which compressors come to action at what time. Depending on the type of compressor and air demand, different types of control exist. It can do a “Load-Unload” control if it is a fixed speed compressor. Since the compressor has fixed speed, it always produces the same amount of air. To meet the air demand and pressure difference created in the users, there is valve which closes and opens in order to restrain air flow or to let it flow through the pipes. Compressors can also be controlled via “Variable Speed Drive (VSD)” devices. The second type of control is much more efficient than the first. Apart from this there is also the matter of starting the compressor. The next figure shows a comparison of the different ways of doing it.

Pressure drop in a distribution network is very frequent and, in some way, inevitable. This represents a big portion of the costs of a CAS. In order to satisfy the needs of the

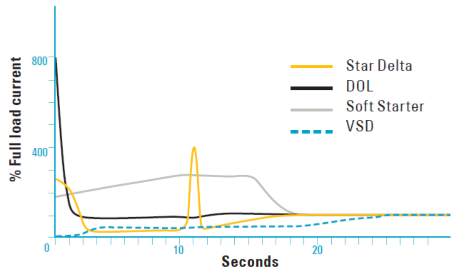

Figure 3 - Compressor Starting Methods [9]

A.1 Common Opportunities for Improvement

In a study on CAS efficiency, Dindorf et. al found 17 points of potential improvement, going from cleaning and location of the compressors aspects, until more technical ones such as valves and dryers [10]. Other studies say that CAS efficiency depends mainly on six points: air leakage, pressure drop, electric motor efficiency, VSD, Heat Recovery Units and entering air temperature [11, 12].

VSD´s are the best way to reduce the consumption of an electric motor. Most of the motors were developed to work at nominal speed, being optimized only for certain value of rotation speed. Installing a VSD can give place to savings up to 50%, reduce the need for maintenance and increase the compressor's useful life.

Up to 90% of the energy used by the compressor is converted in Heat. A well designed system to perform recovery of the otherwise wasted heat can recover from 50 to 90% of this heat. Typical uses for the heat concern spaces or water heating.

Electric Motors are the big responsible for electricity consumption in a CAS. Ordinary motors have efficiencies of around 80% and some can reach 90% at full load. However, manufacturers have been able to increase these values by improving the isolation of the rotor, efficiency of the fan and the quality of the steels used. In 2005, the European Commission has divided electric motors according to their efficiency: EFF_1, EFF_2 *e* EFF_3. These motors have smaller need of maintenance, higher lifetime and are more reliable. At a European level, changing for this type of motors could result in 202 billion kWh saved, which is the same as saying 10 billion euros and 79 millions of tons of CO_2 emissions.

B. Cogeneration

Cogeneration (CG) is the combined cycles of production of heat and electricity. Their products – electricity and processes, the compressor has to produce pressure high enough to, after accounting the pressure drops, deliver the air in desired conditions. Every additional bar in pressure of air produced represents more 7% of energy consumption. These losses exist because of the increase in flow speed and therefore turbulence. They are also affected by the geometry of the pipes. The pressure drop can be calculated as follows [13]:

$$\Delta P = f \times \frac{Q_v^{1.85} \times L}{d^5 \times P} \; [bar] \qquad (1)$$

Where f represents the friction factor, which typically assumes the value of 280 for Aluminum and 450 for galvanized steel. Q_v is the air flow in *Free Air Delivery* (FAD) conditions, meaning a reference temperature of 20ºC, pressure of 1 bar and 0% humidity.

Finally, there is d which represents the diameter of the cross section, P is the production pressure and L the length of the pipes.

Leakages can be responsible of 20-50% loss of compressor power. In the Figure that follows there is a representation of the power lost versus the size of the diameter of the leakage.

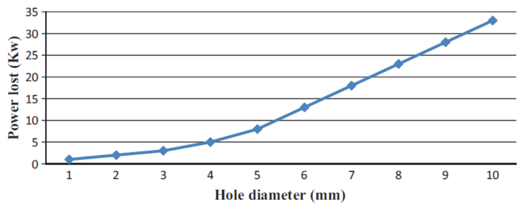

Figure 4 - Power Loss vs. Hole Diameter

There are different methods to measure leakage. The most common one is to measure the flow of air being consumed when there is no need of compressed air in the equipment's. This way a depression is created and all the air being produced to "fight" that depression is feeding leakages. According to Marshall et. al [14], leakages can also be measured using the following expression:

$$L\;(ft^3/min) \;=\; 1.25 \times \frac{V \times (P_1 - P_2)}{T \times 14.7} \qquad (2)$$

B.2 Technologies Used

There are several types of technologies to do CG. These can be divided into 2 categories: *topping* or *bottoming*. Only steam – are different results from a single input: the burned fuel. The activity of CG should be prioritized to fulfill the thermal demand of the processes. It can have efficiencies up to 90%, which represents a 35% economy when compared to the conventional system of heat. Besides offering a great energetic efficiency and few losses in transmissions, this is one of the better ways to reduce the emissions of CO_2. On the other hand, this systems require big investments and care for maintenance [15, 16].

B.1 Sizing Methodology

The sizing of the CG unit is based on the thermal and electric demand profiles. It should be sized in conditions that minimize the fixed and operation costs related with fuels, boilers and turbines as well as savings from taxes regarding emissions and electric energy sold or auto consumed [17]. The most common method for sizing is the method of the maximal area. Having the thermal power demand in a year (8760 hours), the power chose is the one that maximizes the area below the demand profile.

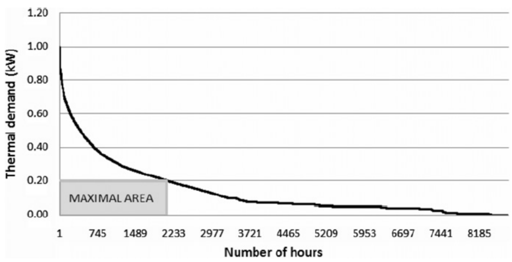

Figure 3 - Method of the Maximal Area [18]

Arcuri et. al [19]. developed a nonlinear program, with which they concluded that the efficiencies of CG units are directly proportional to the installed power. They named it the *Scale Effect.* They discovered that this effect is not applicable only for the Fuel Cells technology because of its modular properties. One of the most critical aspects when sizing a CG unit is the deterioration of its efficiency when it's operating at partial load. Another conclusion that can be taken from this study is that the price of installing and operating ($€/\mathrm{kW}$) lowers when the power increases.
Steam is produced at high pressure in a boiler where the water temperature is superior to the saturation temperature and then feeds the turbine responsible for electricity production. This turbine has to be designed to meet the process steam needs. Typically, this type of *topping* systems are used nowadays. In this systems, the fuel is used first to produce electricity and second to produce heat. The choice of which technology to use depends on factors such as range of power demand, fuel type and the use of heat [20]. In the case where steam at high pressure (> 3 bar) is required for the processes, there are only three possibilities for the cogeneration cycle: Brayton, Rankine or Combined.

B.2.1 Gas Turbine – Brayton Cycle

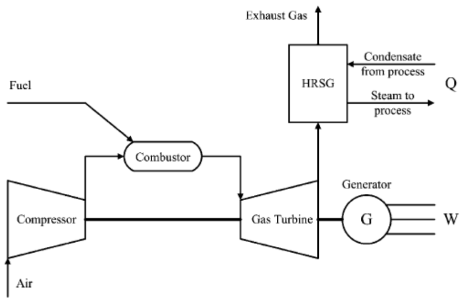

Figure 4 - Brayton Cycle [21]

This type of technology is generally used on large scale CG units due to its reliability and wide power range. The combustor burns the fuel at constant pressure. Afterwards, the gases leave the gas turbine at a temperature around 500 ºC and are expanded to produce work. Installing a Heat Recovery Steam Generator (HRSG) will allow to use steam for the processes.

B.2.2 Steam Turbine – Rankine Cycle

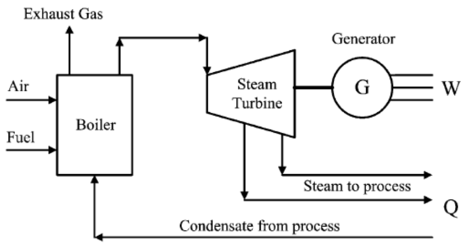

Figure 5 - Rankine Cylce [21]

The Steam Turbine can present two types of configuration depending on its output pressure: "Counter pressure", where the pressure is superior to atmospheric or "Extraction" where it is inferior.
This parameter helps to evaluate the CG unit in comparison to the traditional way of producing heat and electricity.

B.3.2 Economic Indicators

systems produce thermic energy 5 times more than electric.

B.2.3 Combined Cycle

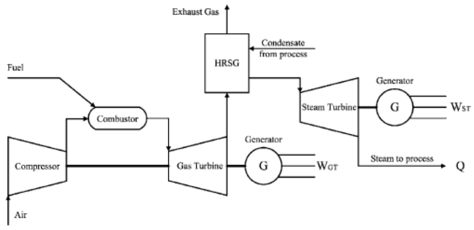

Figure 6 - Combined Cycle [21]

This system consists of a combination between the previous two mentioned. In this case in particular, there is a two-step process for the production of electricity. This is one of the big advantages of this kind of system because it allows to maximize the electric efficiency comparing to the other two. The advantage of such systems is that it needs a big investment.

B.3 Performance Indicators

B.3.1 Energetic Indicators

One of the important indicators in a CG unit is the ratio between the heat, Q, and electricity, E, produced. It is defined as $\gamma_{CG} = \frac{Q}{E}$ and it can have values from 1 to 4 in Rankine cycles and between 0,5 and 1,5 in Brayton cycles [22]. The global efficiency of the system can be defined as: $\eta_G = \eta_E + \eta_Q = \frac{Q+E}{C}$ where C stands for the energy supplied by the fuel, having in consideration its Lower Heating Value (LHV).

Another important indicator is the Equivalent Electric Efficiency (EEE): $EEE = \frac{E}{C - \frac{Q}{0{,}9 - 0{,}2 \times \frac{CR}{C}}}$ where CR is the energetic equivalent of renewable sources of energy in the CG installation. In order to be worth of investing in a CG project, EEE must be at least 0,55. Finally, there is Primary Energy Savings (PES) and it is defined as $PES = \left(1 - \frac{1}{\left(\frac{CHP\,H\eta}{Ref\,H\eta}\right) + \left(\frac{CHP\,E\eta}{Ref\,E\eta}\right)}\right) \times 100\%$.

In order to evaluate a project of CG besides from the energetic point of view, it is important to analyze some economic indicators as well. Four variables are defined: Net Savings (NS), Net Present Value (NPV), Internal Rate of Return (IRR) and Payback Period (PP).

$$NS = Costs_{Conventional} - Costs_{CG}$$

The conventional costs to meet the thermal demand of the processes are basically the costs of operating the boiler and the cost of buying the fuel (typically Natural Gas). This cost of buying Natural Gas is defined in the Portuguese law and depends on several factors such as consumption, occupancy of lands and some fixed terms. As for the CG costs, they are higher than the conventional ones, but to do the economic analysis it must also be taken into account the value in electricity (sold or auto consumed) and the attribution of prizes concerning high efficiency and renewable energies incorporation, which are defined by the Portuguese government by law.

$$NPV = \sum_{i=0}^{n} \frac{NS_i}{(1+t)^i} - I$$

The NPV indicates the viability of a project. In order for it to be an interesting one, it should always be greater than zero. In this case, the Cash Flows considered are the Net Savings and t represents the rate of discount.

$$I = \sum_{i=0}^{PP} NS_i$$

The Payback Time is, as the name shows, the time needed for the cash flows to match the investment. At this time, NPV is zero.

$$0 = \sum_{i=0}^{n} \frac{NS_i}{(1+IRR)^i} - I$$

Finally, the IRR is the return tax that a project should have in order to recover its investment over a period of n years.

III. Case Study

1. Compressed Air System

Which, since there is no heat recovery unit, consists in the ratio between produced air and consumed electricity to do

The CA unit is composed by five "Oil Free – Rotary Screw" compressors. Compressors 3 and 5 have VSD (132 kW and 160 kW) and the other three (225 kW) have fixed rotation speed. The produced pressure of the air is around 6,5 bar and usually at a volume rate of 1500 liters per second, which is about 60 to 70% of the system capacity (Compressor 2 is usually stopped). There is also an air reservoir with 6 cubic meter capacity which function is to neutralize the pressure peaks.

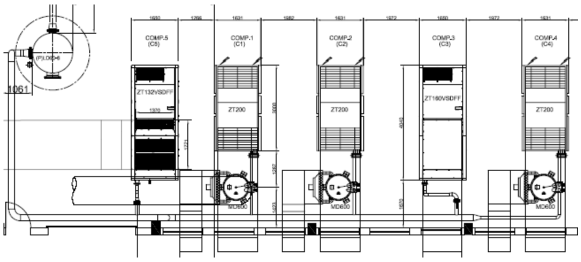

Figure 7 - CAS layout

The distribution pipes are made of stainless steel and have a cross section diameter from 25 to 200 millimeters. The compressors have two stages of compression: the first one compresses the air from atmospheric pressure to about 2,5 bar and the other takes it to 7 bar. The considered production pressure is 6,5 bar because between the compression outlet, the air goes through the dryer and incurs in some pressure losses.

The production levels are more or less constant from Monday to Friday) and vary a bit on Saturdays, but are almost always zero in Sundays. Consumed power varies in the same way as produced air:

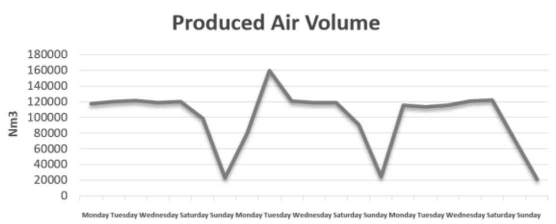

Figure 8 - Compressed Air Production Volume

In order to understand how the CAS is performing, it is important to define an indicator. The performance ratio is defined as:

$$EFoper = \frac{\mathrm{EVCA(L1)}}{\mathrm{EVele(CA,L1)} - \mathrm{EVHE(CA,L1)}}\ [\mathrm{N}m^3/\mathrm{kW}]$$

so. The value of this ratio in the studied month was of *7,2*. When benchmarked with other factories, and comparing to the values announced by the manufacturers, this value was found to be quite low. Although there were electricity consumption meters in each compressor, one of the difficulties found to understand if each compressor was being efficient or not was that the flow measuring system was placed in a pipe where all 5 compressors flow were already mixed. Since at the exit of each compressor there is a 90º elbow, measuring the air flow with meters wouldn't be precise due to the existence of turbulence. The solution found was to test compressors individually in the week of shutdown of the factory. This way, the values measured on the global system corresponded to the compressor in use at the time. The only problem with these measures was that they didn't correspond exactly to the working conditions and, because of this, in the fixed speed compressors, they constantly entered in Load/Unload as shown in the Figure below.

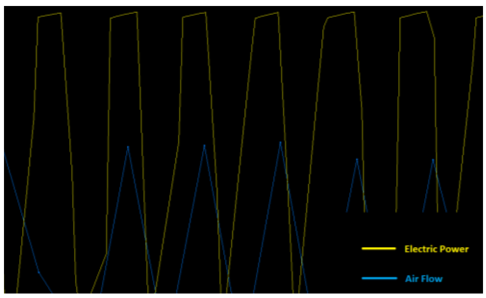

Figure 9 - Load Profile Fixed Speed Compressor

Regardless, an estimation was made with the top values of kW consumed and volume of air produced and the performance ratios and pressure drop on the dryers per compressor were:

Table 1 - Compressors Efficiency Ratio

Comp.	1	2	3	4	5
Nm3/kWh	7,1	7,0	8,2	6,3	8,4
ΔP (bar)	0,2	0,2	-	0,4	-

Compressors 3 and 5 don't have values for the pressure drop in the dryer because in these compressors, air dryer is incorporated.

In order to evaluate the validity of the measures presented in the table, an error can be defined as:

$$e(\%) = \frac{(0{,}68 \times 6{,}7 + 0{,}15 \times 8{,}2 + 0{,}17 \times 8{,}4) - (7{,}2)}{7{,}2} \times 100 = \ 0{,}2\ \%$$

Where 0,68 corresponds of the weight in volume produced by compressors 1 and 4, 0,15 the weight of air volume produced by compressor 3 and 0,17 by compressor 5. This way, the approximations taken were pretty acceptable.

Concerning the heat recovery unit, since the compressors are air refrigerated, the only viable solution is to make direct connection from the exhaust gases that come from the compressor to pre-heat the combustion gases in the boilers room, which is close by. The conducted study showed that exhaust gases temperature from one compressor are about 40 ºC. Directing this air to the admission of the combustion chamber will provide a rise of 15ºC of the Stack Temperature, which results in a 0,6% improvement in the boiler efficiency.

Theoretical pressure drop was calculated using equation (1) and was compared to the real one and they matched. ΔP is about 0,5 from production until usage in the most distant points, which is acceptable (less than 10%).

2. Cogeneration

Since CG is the combined production of heat and electricity, the first thing to do is describe the heat demand. To do so, the fuel consumptions and boiler efficiency must be known. The boiler in question produces saturated steam at 10 bar and 200 ºC, with a flow rate between 3 and 6 tons per hours. The fuel used is natural gas, which is considered to have a LHV of 10,69 kW/Nm3. The efficiency is given by:

$$\text{Total Steam System Efficiency} = \frac{[\text{m}\ (\text{h1} - \text{h2})]}{[\text{E}(\text{EL}, \text{ST}, \text{L1})\ +\ \text{E}(\text{TH}, \text{ST}, \text{L1})]}\ (\%)$$

Where h1 and h2 represent the enthalpies of steam and feed water respectively, m the mass of steam and the denominator the input in kW by Natural Gas and Electricity used to power the boiler. By the steam tables [15], the efficiency of the boiler gives 85,5%, which is a good value. As it was done for the CAS, the thermal and electrical demand were studied throughout an entire year and it was found that the average electrical consumption was 2900 kW_e and the thermal was 1500 kW_T.

If the company is willing to invest, there are also a few measures to improve CAS efficiency. The one with the

Since the electrical demand is much higher than the thermal, makes sense to level the CG unit with the thermal demand in order to minimize wasted energy.

The thermal profile was obtained multiplying the power input by the fuel with the boiler efficiency.

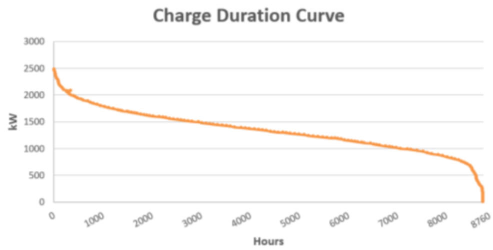

Figure 10 - Thermal Charge Duration Curve

IV. Results and Discussion

Note: In this Chapter, the considered electricity price was 0,1 €/kWh with a conversion of 0,215 kgoe/kWh and for Natural Gas 0,48 €/Nm3 with a conversion factor of 1,077 kgoe/kg.

1. Compressed Air System

As it can be seen, the proposed measures were subdivided in two sections: With and Without Investment. The first measure without investment regards the compressor left in standby. The system only uses 4 of its 5 compressors to meet the process demand. Usually, compressor #2 is the one that is not working. However, after tests were conducted, it was concluded that it should be #4 instead of #2. This change alone will produce a big difference at the end of the year since fixed speed compressors consume an electric power of around 245 kW. The second measure was proposed after an analysis on the behavior of the control system over the fixed speed compressors on weekends. Since the demand is much lower during the weekend, there is no need to use any of the fixed speed compressors because the two VSD alone will meet this demand (capacity up to 2900 Nm3/h). So, setting the control system to use only VSD at the weekends will incur in considerable savings as well. This measure has been implemented by a redefinition of the pressure set points and pressure band. It was defined a pressure band for weekends and another one for week days. This was done because the machines that consume compressed air used during the weekends require a lower pressure than those that operate during the week.

highest impact is changing one fixed speed compressor for a centrifugal one. This new compressor has the capability of producing up to 5300 Nm3/h and a minimum of 4000, with a performance ratio of 12 Nm3/kWh. This would represent an improvement of over 50 % comparing to the existing compressors. Given that the centrifugal will be working 88% of the time, and at other times the existing VSD will work, the global annual average ratio will be 10,9. Despite this, the best option is to substitute one of the fixed speed compressors for a larger VSD because the centrifugal option requires a circuit for cooling water and additional installation costs. To all this calculations using performance ratio, for an "economic safety" point of view, the values used were quite conservative.

The heat recovering unit, as said before, leads to a 0,6% improvement in the boilers efficiency (Figure 11). Since almost all the pipes already exist "*in-house*", the 3000€ investment is needed only to pay the man working hours and some ducts. Although this measure is inserted in the CAS, the savings are in Natural Gas consumed by the boiler, instead of electricity consumed by the compressors.

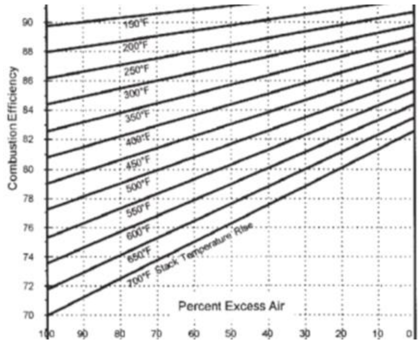

Figure 11 - Boilers Efficiency vs. Stack Rise Temperature

Table 2 - Improvement proposals for CAS

Without Investment

	Savings (€)	Savings (toe)	*NPV (€)*	*IRR (%)*	*PP (years)*
Standby Comp. change	7 900	17,1	-	-	0
Control System Optimization	12 000	26,4	-	-	0

With Investment

	Investment	Savings (€)	Savings (toe)	*NPV (€)*	*IRR (%)*	*PP (years)*
Centrifugal Comp.	370 000	111 575	239,9	351 040	29,5	3,3
VSD Comp.	190 000	51 797	111,4	144 740	26,4	3,7
Heat Recov. Unit	5 000	6 740	12,8	38 550	134,8	0,8

2. *Cogeneration*

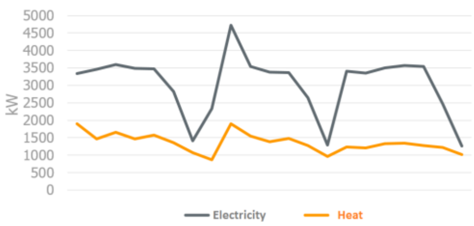

Figure 12 - Power Demands

Since the electrical power never comes below 1000 kW and the average thermal power is about 1500 kW, it makes sense to level the CG plant to meet the thermal demand.

The steam produced has a flow rate of 0,95 kg/s, at 10 bar and 190 ºC. Since the most advantageous model was the Gas Turbine, only that one will be approached in this paper. In the table below Brayton and Rankine are compared. Combined cycle isn't contemplated due to the high values of investment and maintenance making it difficult to implement in the industrial unit. The values in Figure 13 can be explained with a quick energetic analysis. It is assumed that $(P_4/P_3) = (P_1/P_2)$ and the values of efficiency of compressor (0,82), generator (0,97), turbine (0,85) and combustion chamber (0,98) are constant.

This being said, the CG study was based on the principle that the outcome of the plant is Steam.

To calculate the work done by the compressor and the turbine, it is important to know the inlet and outlet temperatures (T_2):

$$T_{2s} = T_1 \left(\frac{P_2}{P_1}\right)^{(\gamma_{air}-1)/\gamma_{air}} \rightarrow T_2 = T_1 + \frac{1}{\eta_c}(T_{2s} - T_1) \quad (3)$$

Where T_{2s} is the isentropic outlet temperature of the compressor and T_2 the real temperature.

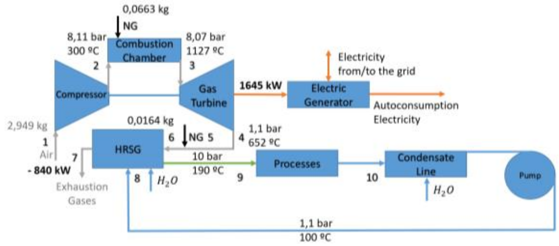

Figure 13 - Gas Turbine Cogeneration

The work done by the compressor (- 840 kW) is:

$$W_C = \dot{m}_{air} C_{p,air}(T_1 - T_2) \quad (4)$$

Doing an energy and mass balance, it is possible to correlate the flow rates of gases, natural gas and air:

$$\dot{m}_{gas} = \dot{m}_{GN} + \dot{m}_{ar} \quad (5)$$

$$(\dot{m}_{NG} + \dot{m}_{air})C_{P,gas}(T_3 - T_0) + \dot{m}_{gas}(LHV_{NG})(1 - \eta_{CC}) = \dot{m}_{gas}(LHV_{NG}) + \dot{m}_{air}C_{P,air}(T_2 - T_0) \quad (6)$$

To calculate the produced electricity by the turbine, it is important to know T_3 and T_4:

$$T_{4s} = \frac{T_3}{P_4/P_3(1 - f_{pd})^{\left(1-\frac{1}{\gamma_{gas}}\right)}} \rightarrow T_4 = T_3 + \eta_{gt}(T_3 - T_{4s}) \quad (7)$$

$$W_{gt} = \dot{m}_{gas} C_{p,gas}(T_3 - T_4) \quad (8)$$

The amount of steam produced without supplementary firing is calculated as follows:

$$Q_{evap} = \dot{m}_{gas} C_{p,gas}(T_9 + 8{,}33 - T_6) \quad (9)$$

$$\dot{m}_{steam} = \frac{Q_{evap}}{(h_9 - h_8)} \quad (10)$$

Since this value isn't enough to feed the processes, a supplementary firing of Natural Gas is required, as shown in Figure 13. The amount of NG to burn is calculated by the boiler efficiency, the fuel LHV and the enthalpy of saturated steam at 10 bar. In Table 3 the summary of both Steam and Gas Turbine CG systems is presented.

Apart from the benefits of auto consuming the produced electricity, the Portuguese government also encourages CG activity by giving efficiency and renewable energies prizes. Since the factory in is to have 5% of electricity from Photovoltaic cells:

	Efficiency Prize	Renewables Prize
Rankine	20 160	748
Brayton	90 868	6 991

On the other side, it is more profitable to consume all the produced energy and in that situation there are no contemplated prize attributions.

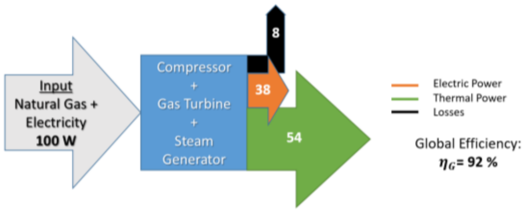

Figure 14 - Global Efficiency of Cogeneration

Conclusion

In conclusion, there is a great room for improvement in what concerns energetic efficiency. Measures proposed on the CAS would provide a 13 % improvement in this system which would represent 2 % of the factory overall. As for the Cogeneration, this measure has more impact. It would lead to a 14 % overall factory energetic efficiency improvement. Having the opportunity to implement both measures, energetic efficiency on a global level would increase by 17,2 %.

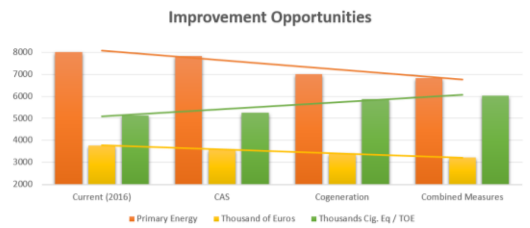

Figure 5 - Efficiency Measures

Table 3 - Cogeneration Parameters Option per Technology

	$^{kW_e}/_{kW_T}$	*NS* (€)	*Inv.* (€)	*NPV* (€)	*IRR (%)*	*PP (years)*	*PES (%)*	*EEE (%)*	*Toe*
Brayton	1:2,8	365 000	1 370 000	1 100 310	31,9	3,6	21,4	95	1005,4
Rankine	1:13	115 000	530 000	308 650	21,8	4,6	15,8	89	267,4

Acronyms

CAS Compressed Air System

CG Cogeneration

EEE Equivalent Electric Efficiency

FAD Free Air Delivery

HRSG Heat Recovery Steam Generator

IRR Internal Rate of Return

NPV Net Present Value

NS Net Savings

PES Primary Energy Savings

PP Payback Period

TOE Ton of Oil Equivalent

VSD Variable Speed Drive

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