Study and implementation of a cogeneration power plant in a Portuguese factory

Fernando Daniel Leocádio Campos Nunes

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Electrical and Computer Engineering

Supervisor(s): Prof. José Manuel Dias Ferreira de Jesus

Prof. Mário Manuel Gonçalves da Costa

Examination Committee

Chairperson: Prof. Célia Maria Santos Cardoso de Jesus

Supervisor: Prof. José Manuel Dias Ferreira de Jesus

Members of the Committee: Prof. Rui Manuel Gameiro de Castro

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Declaration:

I declare that this document is an original work of my authorship and that it fulfills all the requirements of the Code of Conduct and Good Practices of the Universidade de Lisboa.

I dedicate this thesis to my grandmother Alice.

Abstract

Cogeneration is the simultaneous generation of multiple forms of useful energy, in most cases, electrical and thermal energy, in an integrated system, using a single fuel source. Although cogeneration processes were already in use several years ago, it was only from 2008 that cogeneration experienced the highest growth and utilization in the Portuguese industry. This growth was mainly due to measures taken to ensure that industrialists could use more environmentally friendly systems that allow them to rationalize resources. These measures are even more important today. Another major factor that benefits cogeneration projects is financial profitability they are associated with. This is because through the same primary energy source, it allows us to produce thermal and electrical energy, thus rationalizing resources. However, this financial profitability is dependent on a number of factors, notably the price of fuel and electricity. Although cogeneration is already well developed and there are technologies that allow users to achieve good results in its operation, new technologies are still being developed, so-called emerging technologies, which promise to improve cogeneration exploitation results and increase profitability.

The purpose of this study is to examine the cogeneration project, taking available technologies and primary energy sources in account, that best apply to a specific case study (at the company Pinewells) from a technical, environmental and economic point of view.

Keywords: Cogeneration, self-consumption, biomass, natural gas, industry, profitability.

Resumo

A cogeração é a geração simultânea de múltiplas formas de energia útil, na maioria dos casos, energia elétrica e térmica, num sistema integrado, utilizando uma única fonte de combustível. Embora os processos de cogeração já estejam em uso há vários anos, foi somente em 2008 que a cogeração teve o maior crescimento e utilização na indústria portuguesa. Esse crescimento deve-se principalmente às medidas adotadas para garantir que os industriais pudessem usar sistemas mais ecológicos, que lhes permitissem racionalizar recursos. Essas medidas são ainda mais importantes nos dias de hoje. Outro fator importante que beneficia os projetos de cogeração é a rentabilidade financeira à qual estão associados. Isto ocorre porque, através da mesma fonte de energia primária, nos permite produzir energia térmica e elétrica, racionalizando recursos. No entanto, essa lucratividade financeira depende de vários fatores, principalmente do preço do combustível e da eletricidade. Embora a cogeração já esteja bem desenvolvida e existam tecnologias que permitem aos utilizadores obter bons resultados na sua operação, existem novas tecnologias que ainda estão a ser desenvolvidas, as chamadas tecnologias emergentes, que prometem melhorar os resultados de exploração da cogeração e aumentar a lucratividade.

O objetivo deste trabalho é estudar um projeto de cogeração, levando em consideração as tecnologias disponíveis e as fontes de energia primária, que melhor se aplicam a um estudo de um caso prático (na empresa Pinewells) do ponto de vista técnico, ambiental e económico.

Palavras-chave: Cogeração, auto-consumo, biomassa, gás natural, rentabilidade.

Acknowledgments

This thesis is the culmination of 5 years of hard work and effort. These were fantastic years and these memories will be with me for the rest of my life.

Firstly, I want to dedicate this thesis to my closest family, my parents, my grandmother and my brothers, João and Francisco, who helped me to better balance my academic life with my social life. They were all very understanding with me and supportive during difficult moments.

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List of Acronyms

PRE	*Produção em Regime Especial* [Special Regime]
RESP	*Rede Elétrica de Serviço Público* [Electrical Network of Public Service]
PCI	*Poder calorifico inferior* [Lower value]
IRR	Internal Rate of Return
NPV	Net Present Value
ISP	*Imposto Sobre Produtos Petrolíferos e Energéticos* [Tax on oil and energy products]
EBITDA	Earnings before interest, tax, depreciation and amortization
WACC	Weighted average cost of capital
CIEC	*Código dos Impostos Especiais de Consumo* [Code of Special Consumer Taxes]
CELE	*Comércio Europeu de Licenças de Emissão* [European Emissions Trading]
NIM'S	National Implementation Measures
GHG	Greenhouse gas

1. Introduction

This thesis aims to implement a cogeneration system in an industrial unit, with the main goal of rationalization and useful management of resources. The main objectives, motivations and outline of this document are presented in this chapter.

The project developed had the support of the company Pinewells, which is the industrial unit where the project was performed, and Ambitermo, which is a company specialized in energy production systems.

1.1 Motivation

Energy production and self-sustainability are increasingly prevalent factors today. Funding and incentives exist for raising awareness of the importance of the environment and advocating the rational and responsible use of fossil fuels, leading to a number of actions to save energy and reduce the impact of energy systems.

There are two main objectives when the issue is to reduce greenhouse gas emissions. The first is to promote the use of renewable resources, while the second is to develop and to improve the national production sector with a view to improving energy efficiency.

One of the possible solutions to meet the requirements mentioned above is investment in cogeneration plants. These are characterized by being systems of simultaneous decentralized production of electric and thermal energy from the same primary source of energy.

1.2 Objectives

The present dissertation aims to study the feasibility of implementing a cogeneration plant in a pellet production plant. One of the main advantages of this project is that it allows for a greater rationalization of resources, and for making the plant more self-sustaining.

Cogeneration technology best fitting this project was studied, as well as the primary energy source, and the results indicating the best solution. Emerging technologies were also studied to conclude whether or not their use makes sense as a solution in this project.

1.3 Problem definition

This project is based on a real situation, where there is a need for reorganizing resources and improving product quality.

The case studied was the Pinewells factory, located in the center of Portugal. This company is one of the largest pellet manufacturing factories in the country, producing some 130,000 ton per year of this product. The objective of the company is to install a cogeneration plant for producing electric and thermal energy, both for self-consumption.

Cogeneration plants become an interesting solution when thermal energy is used. In the case of the present company, drying systems also have a significant weight in the price of the final product. The combination of the two makes a cogeneration project globally more interesting, since it allows for considerable reduction in energy use. Thus, the study compares the proposed solution with the current solution for wood drying.

1.4 Thesis outline

This thesis is organized in six chapters, with this one making up the introduction and providing background. Chapter 2 addresses the evolution of cogeneration in Portugal, several different technologies, as well as primary energy sources that can be used. It also discusses how the use of cogeneration and its environmental impacts can be evaluated.

Chapter 3 presents the case study. The chapter presents the factory where this project will be implemented, as well as the manufacturing process housed there. For a better understanding of the values used in this project, both details of the energy characterization of the plant, and details on the use of the biomass are included.

Chapter 4 presents possible solutions for the practical case. For each of the solutions, its insertion in the manufacturing process is studied, an economic study is performed and, finally, an overall evaluation of the solution is also conducted.

Chapter 5 is dedicated to the general analysis of the solutions from a technical, economic and environmental point of view.

Finally, Chapter 6 summarizes the main conclusions of this work and presents some suggestions for further work.

2. Cogeneration

2.1 The concept

Cogeneration, also known as ”combined heat and power”' (CHP), is the simultaneous generation of multiple forms of useful energy, in most cases, electrical and thermal energy, in an integrated system, using a single fuel source. This primary source can be a fossil fuel, such as natural gas or diesel, or even a renewable fuel, such as biomass or biogas. In either case, the cogeneration process is a much more efficient way of using energy powering such systems that is often associated with renewable energies.

According to Decree-Law no. 186/95, cogeneration is defined as:

“*O processo de produção combinada de energia elétrica e térmica, destinando-se ambas a consumo próprio ou de terceiros, com respeito pelas condições previstas na lei.*” [“The combined production process of electric and thermal energy is both intended for personal consumption or third parties, according to the conditions which are provided by law.”]

The technologies used in cogeneration systems are expected to maximize the savings of primary energy. Fig. 1 illustrates the principle underlying cogeneration, comparing it with the conventional production of separate thermal and electrical energy [1].

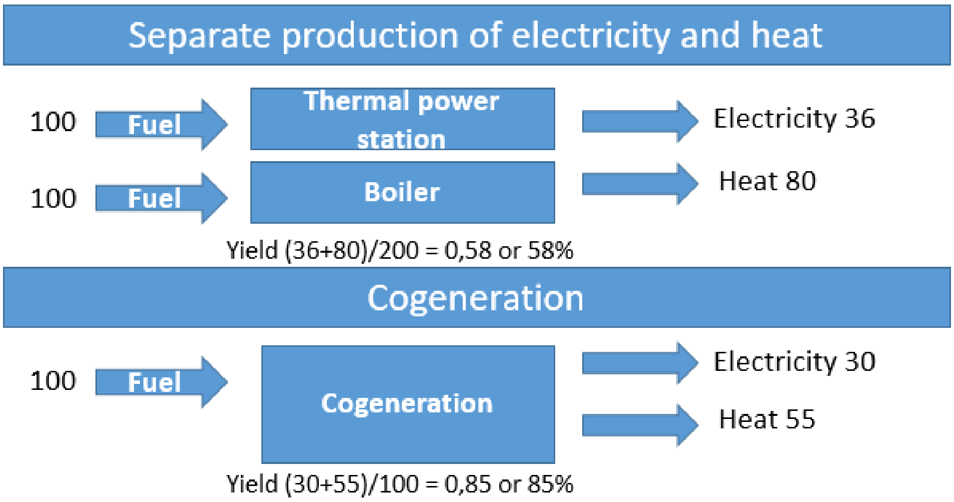


Fig. 1: Comparative energy balance of cogeneration with conventional production [1]

The figure shows that, when produced separately, electricity and heat can be generated by a cogeneration system and, despite some losses, 58% combined profit can be obtained.

A cogeneration unit is considered highly efficient, allowing for values of 25% to be attained in initial energy savings, by dividing verified fuel consumption reduction by the fuel quantity in a conventional solution.

2.2 Evolution of cogeneration in Portugal

Portugal has a long history of using hydraulic turbines and steam powered engines to produce energy, always intended for local consumption. The first technologies of this kind date from the mid nineteenth century for steam engines and in the end of the same century for hydraulic applications – used as purely mechanical or in driving electrical generators naturally operating as in direct current [2]. At that time, hydroelectric and thermoelectric plants gained some popularity among small producers both for industrial and public service.

It was in the middle of the twentieth century, with large hydroelectric projects and the consequent appearance of electricity in urban centers that mechanical energy was substituted by electricity. Then, driving machines started to be carried out directly by three-phase engines [2]. This has resulted in the decline of energy production facilities, for local consumption, in particular for public service.

Fig. 2 reveals that after an average increase at a rate of 118 MW/year since 2007, installed cogeneration capacity reached 1,195 MW in 2013. Since the publication of the DL 23/2010, which introduced a time limit for existing plants to operate as PRE, combined with the publication of DL 25/2012, which suspended the injection of power in the RESP, had a negative impact on the annual production of electricity in cogeneration in 2014, 2015 and 2016. Since 2014, the nonexistence of new power plants to replace those that have been decommissioned, resulted in an installed power lower than that of 2013 [3].

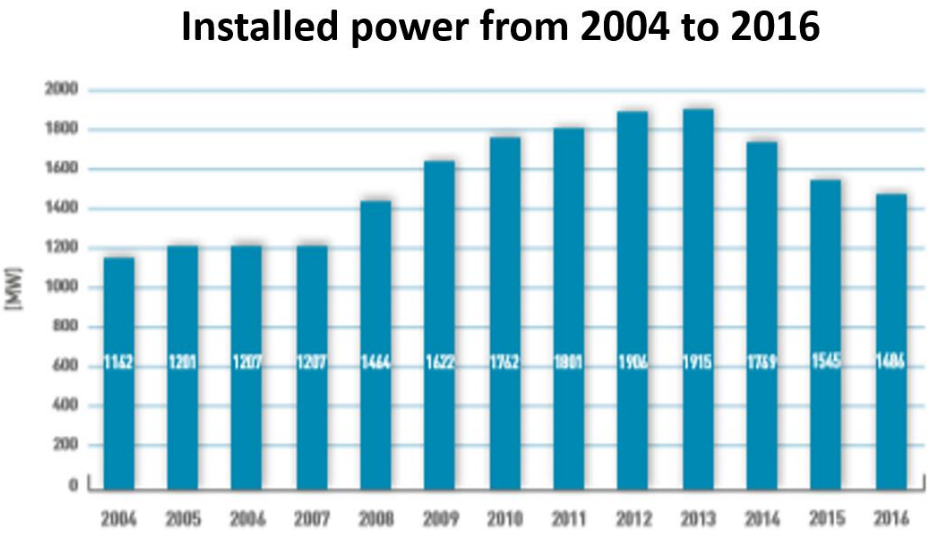


Fig. 2: Capacity installed in cogeneration from 2004 to 2016 [3]

It is also necessary to look at the distribution of the different technologies used by cogeneration activity. According to Fig. 3 the majority of power systems are natural gas turbines. The figure also reveals that both back pressure turbines and fuel oil engines are practically non-existent in Portugal (accounting for 5% and 1% of the total, respectively). Fig. 3 also shows that NG turbines and NG engines account for 68% of the total, which illustrates the importance of natural gas in cogeneration in Portugal. Finally, Fig. 3 indicates that biomass, which is normally associated with the concept of renewable cogeneration, accounts for more than 25% of total cogeneration power plants [4].

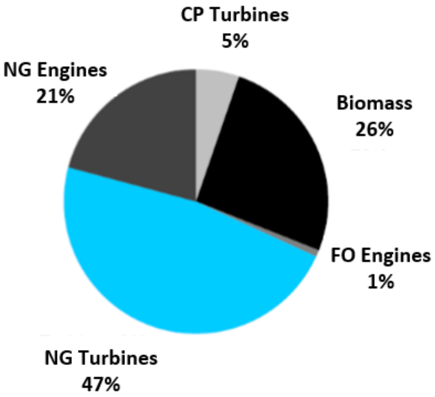


Fig. 3: Cogeneration technologies in Portugal in the year 2013 [4].

Fig. 4 shows the distribution by activity sector of installed cogeneration capacity in Portugal in 2013. It is seen that chemical, paper and textile industries are the ones that most extensively use cogeneration in Portugal. In contrast, the timber industry, where the plant (Pinewells) studied in this work is, accounts only for 1% of the total.

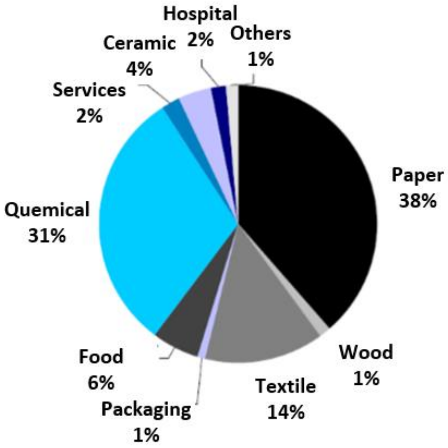


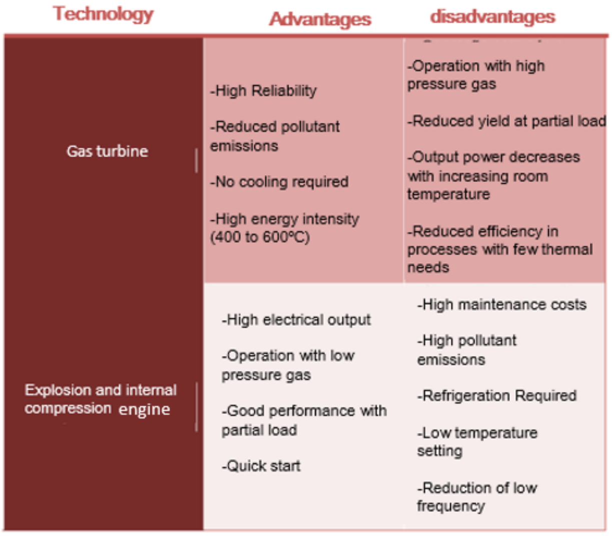
Fig. 4: Distribution by activity sector of installed cogeneration capacity in Portugal in the year 2013 [5].

2.3 Cogeneration technologies

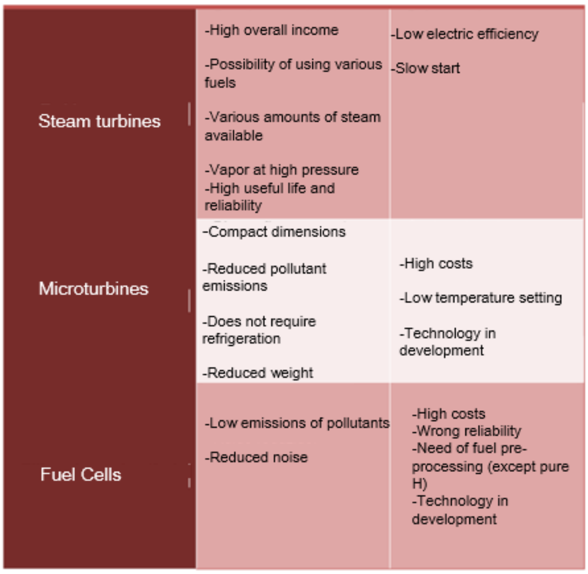
The technological solutions that are currently used in cogeneration systems can be divided into two distinct groups, which are related to the degree of maturity, technological development and commercial dissemination. The two groups are traditional and emerging technologies [6]. The first group includes gas turbines, reciprocating engines and steam turbines, and the second group incorporates micro turbines and fuel cells.

Selecting cogeneration technology for a given project should be subject to careful analysis as it’s dependent on several factors. Each technology has advantages and disadvantages imposed by its own characteristics, which must be taken into account in order to ensure that the choice made is the best possible response to the specific needs of the installation [1].

The factors that should be considered when selecting technology include: average peak conditions of electrical and thermal requirements, the number of hours for these needs, the heat type that will be used, the speed response that is needed, the type, price and availability of fuel that will be used, the commercial availability of equipment, etc. [7]. Table 1 lists the main advantages and disadvantages of different cogeneration technologies [6].



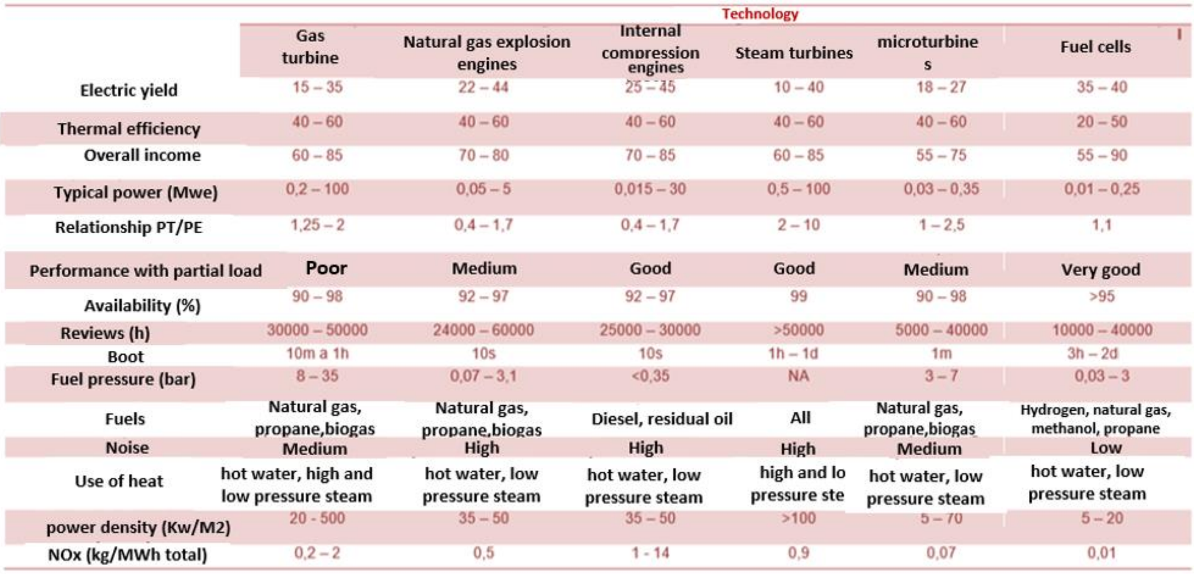
Technology	Advantages	disadvantages
Gas turbine	-High Reliability -Reduced pollutant emissions -No cooling required -High energy intensity (400 to 600ºC)	-Operation with high pressure gas -Reduced yield at partial load -Output power decreases with increasing room temperature -Reduced efficiency in processes with few thermal needs
Explosion and internal compression engine	-High electrical output -Operation with low pressure gas -Good performance with partial load -Quick start	-High maintenance costs -High pollutant emissions -Refrigeration Required -Low temperature setting -Reduction of low frequency



Steam turbines	-High overall income -Possibility of using various fuels -Various amounts of steam available -Vapor at high pressure -High useful life and reliability	-Low electric efficiency -Slow start
Microturbines	-Compact dimensions -Reduced pollutant emissions -Does not require refrigeration -Reduced weight	-High costs -Low temperature setting -Technology in development
Fuel Cells	-Low emissions of pollutants -Reduced noise	-High costs -Wrong reliability -Need of fuel pre-processing (except pure H) -Technology in development

Table 1: Advantages and disadvantages of different cogeneration technologies [6].

Table 2 shows the main technical characteristics of different cogeneration technologies [6].



	Technology					
	Gas turbine	Natural gas explosion engines	Internal compression engines	Steam turbines	microturbines	Fuel cells
Electric yield	15 – 35	22 – 44	25 – 45	10 – 40	18 – 27	35 – 40
Thermal efficiency	40 – 60	40 – 60	40 – 60	40 – 60	40 – 60	20 – 50
Overall income	60 – 85	70 – 80	70 – 85	60 – 85	55 – 75	55 – 90
Typical power (Mwe)	0,2 – 100	0,05 – 5	0,015 – 30	0,5 – 100	0,03 – 0,35	0,01 – 0,25
Relationship PT/PE	1,25 – 2	0,4 – 1,7	0,4 – 1,7	2 – 10	1 – 2,5	1,1
Performance with partial load	Poor	Medium	Good	Good	Medium	Very good
Availability (%)	90 – 98	92 – 97	92 – 97	99	90 – 98	>95
Reviews (h)	30000 – 50000	24000 – 60000	25000 – 30000	>50000	5000 – 40000	10000 – 40000
Boot	10m a 1h	10s	10s	1h – 1d	1m	3h – 2d
Fuel pressure (bar)	8 – 35	0,07 – 3,1	<0,35	NA	3 – 7	0,03 – 3
Fuels	Natural gas, propane,biogas	Natural gas, propane,biogas	Diesel, residual oil	All	Natural gas, propane,biogas	Hydrogen, natural gas, methanol, propane
Noise	Medium	High	High	High	Medium	Low
Use of heat	hot water, high and low pressure steam	hot water, low pressure steam	hot water, low pressure steam	high and lo pressure ste	hot water, low pressure steam	hot water, low pressure steam
power density (Kw/M2)	20 - 500	35 – 50	35 – 50	>100	5 – 70	5 – 20
NOx (kg/MWh total)	0,2 – 2	0,5	1 - 14	0,9	0,07	0,01

Table 2: Technical characteristics of different cogeneration technologies [6].

2.4 Conventional technologies

2.4.1 Steam turbines

The use of steam turbines is the technological option most applied in industries and in heat network systems. In this type of turbine, steam produced in boilers is expanded in the turbine for generating mechanical energy. In addition, exhaust gases are used as process heat.

The operation of this system begins by preheating water in the designated preheater. This water is then directed to the boiler where the energy extracted from the spent fuel is absorbed by the water leading to temperatures high enough to produce vapor at high pressure. This water vapor enters the turbine; it undergoes a powerful expansion causing the energy of the steam to be transformed into mechanical energy, by rotating the turbine, producing useful work. After producing work on the turbine, the steam, now at a lower pressure, termed exhausted steam, is directed to a condenser. In this condenser, the vapor is liquefied, transforming itself into water that then returns to the boiler.

A generator is coupled through a shaft to the turbine, aiming to transform the received mechanical energy into electrical energy. The steam after driving the turbine, as already mentioned, is still under considerable pressure, some of which may be diverted to be used in the process (the other part goes to the condenser).

Steam turbines are divided into two types according to steam pressure at the outlet of the turbine. When the outlet pressure is higher than atmospheric pressure, a backpressure turbine is present (Fig. 5). If the outlet pressure is lower than atmospheric pressure, the turbine is called a condensation turbine, and there is a need for inserting a condenser into the cycle (Fig. 6) [8].

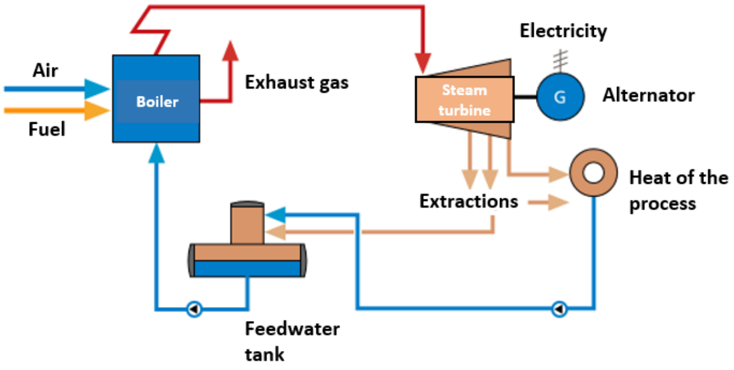


Fig 5: Cogeneration scheme with a backpressure steam turbine [1].

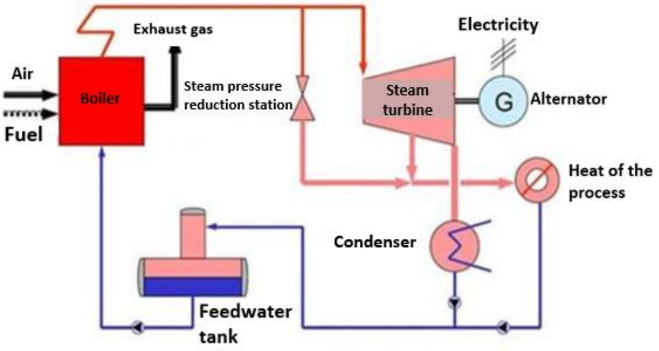


Fig. 6: Cogeneration scheme with a condensation turbine [1].

2.4.2 Gas turbines

A gas turbine is a rotary engine that extracts energy from the flow of a gas stream. Upstream of the combustion chamber, there is a compressor, which is coupled with the turbine by a shaft. Energy is released when air is mixed with the fuel in the combustion chamber and ignition occurs. The resulting gases are directed to the blades of the turbine, promoting their movement. The theoretical working principle of the gas turbines is based on the Brayton cycle, also known as the Joule cycle [9]. The thermal energy from fuel gases, leaving the turbine, may be recuperated in heat recovery boilers.

In systems using a cogeneration scheme with a gas turbine (Fig. 7), heat recovery is made entirely from exhaust gases in a single recovery boiler and there is no need for resorting to heat recovery from water and lubricating oil cooling circuits.

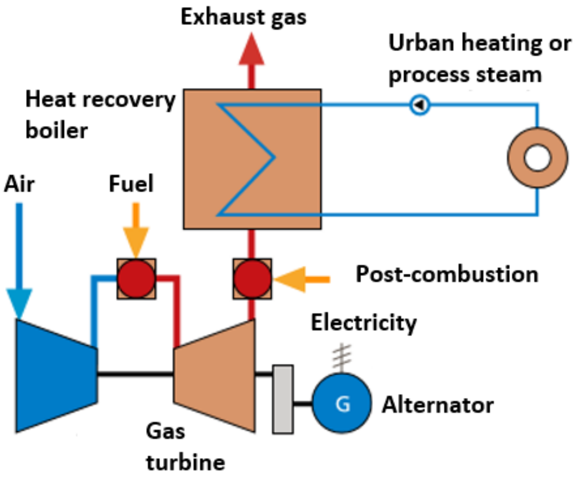


Fig. 7: Cogeneration scheme with a gas turbine.

2.4.3 Internal combustion engines

Internal combustion engines are more popular in scenarios where thermal requirements are not significant, as is the case of the tertiary sector and in small industries. In general, this type of technology (Fig. 8) presents a superior thermal efficiency as compared to other technologies, such as gas and steam turbines, although it also has a series of restrictions related to heat recovery, due to low temperature levels. The feasibility of using engines in cogeneration is limited to certain cases in which the working process requires a relatively large amount of heat at low temperatures. The amount of recoverable heat depends on the engine type, whether the engine is turbocharged or naturally aspirated and on its operating regime.

In an Otto engine, a mixture of air and fuel is compressed in each cylinder and an external spark triggers the ignition. In a Diesel engine, only air is compressed in the cylinder, as fuel is injected in the final phase of compression, with spontaneous ignition occurring due to the high temperature of compressed air.

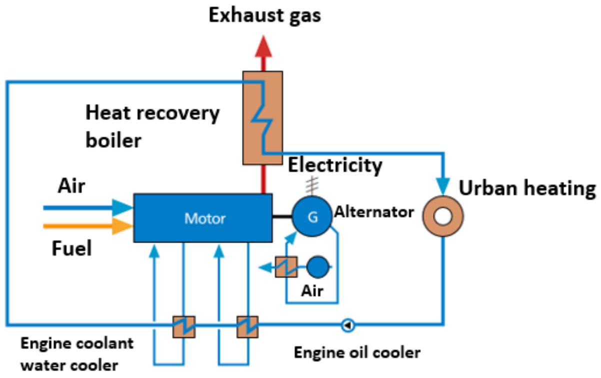


Fig. 8: Cogeneration scheme with an internal combustion engine [10].

In combustion engines the generation of electrical power is guaranteed by coupling a generator to the engine central shaft; thermal energy is recovered from the high temperature exhaust gases, and from the cooling system [11].

2.5 Emerging technologies

2.5.1 Micro turbines

The term "micro-turbine" is usually refers to a relatively small system consisting of a small compressor, combustion chamber, turbine and electric generator, in most cases with a total power generation of lower than 250 kW [10].

Micro-turbines (Fig. 9) are, basically, gas turbines, with an expansion floor. In order to increase the efficiency of the turbine it is customary to incorporate a heat recover system in the system, that allowing for available heat in the exhaust gases to be used to heat fresh air before it enters the combustion chamber.

Fresh air is fed into the turbine at a high speed and high pressure, then mixed with the fuel and burned in the combustion chamber, where the process is controlled for maximum efficiency and low emission levels. The gases produced in combustion expand in the vanes of the turbine producing work. Subsequently, the gases are exhausted into the atmosphere.

Micro-turbines are ideal for distributed power generation due to their high flexibility and possibility to be used in parallel to meet higher needs. They also have the capacity to provide stable energy and low greenhouse gas emissions. As for limitations, micro-turbines present high costs, low electrical efficiency and are sensitivity to environmental conditions.

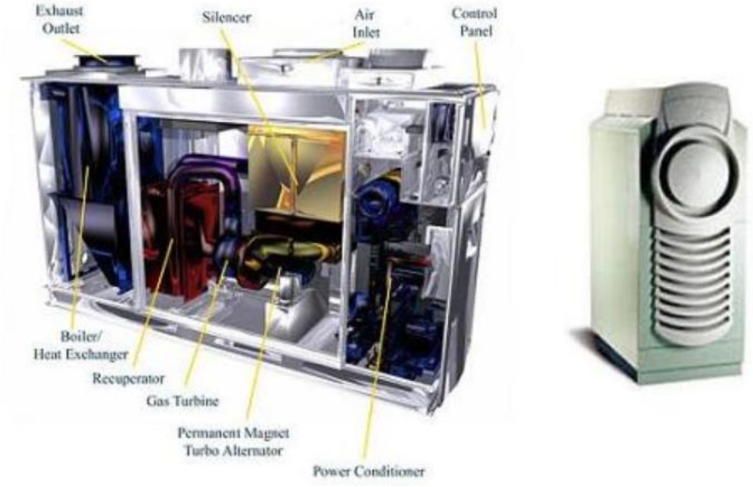


Fig. 9: Typical components of a micro-turbine [12].

2.5.2 Fuel cells

There is already a relatively long experience using fuel cells and considerable knowledge on the technological capabilities of fuel cells, although their practical implementation has been limited by their high costs and lack of durability. Nevertheless, practical applications of fuel cells have been demonstrated in applications such as space flights and cogeneration units (Fig. 10) [13].

Fuel cells are electrochemical machines that produce electricity by converting chemical energy into electrical power without rotary motion or combustion [1]. This technology provides higher efficiency and lower acoustic emissions than traditional technologies.

Fuel cells are environmentally friendly, do not produce harmful gases that contribute to phenomena such as acid rain, and do not release pollutant gases that endanger the quality of the air.

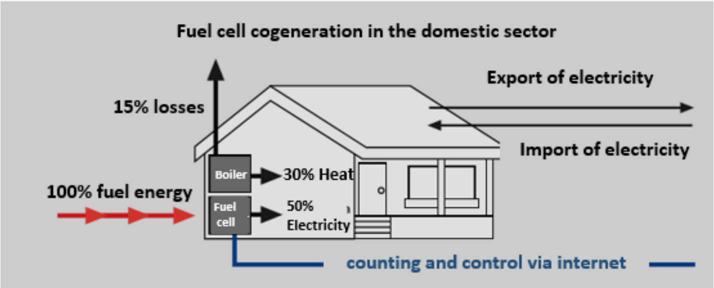


Fig. 10: Cogeneration scheme with a fuel cell [1].

2.6 Primary energy sources used in cogeneration

In general, there are several fuels that are used in cogeneration processes, most notably natural gas, diesel and biomass. Natural gas and biomass are the ones that will have a more important role in the future. Natural gas is one of the fossil fuels that produces less harmful effects on the environment, and biomass is carbon neutral. Table 3 shows the characteristics, like the low heat value, specific mass, CO2 emissions and tonnes equivalent petroleum, of some of the fuels used. [16].

Type of energy	PCI (kJ/kg)	Especific mass (kg/m3)	CO2(kg/GJ)	TEP (tep/t)
Fuel oil	40.170	944,00	77,4	0,984
Natural gas	46.119	0,84	56,1	1,077
Diesel fuel	43.310	837,00	74,1	1,045
Pellets (solid biomass)	16.920	650,00	-	0,401
Chip (solid biomass)	13.320	200,00	-	0,277
Bioethanol (Liquid Biofuel)	26.750	789,30	-	0,645
Biogas (Biofuel gas)	20.934 - 29308	1200 - 1600	-	1,204

Table 3: Some characteristics and properties of some fuel types [17].

2.6.1 Fossil fuels

Fossil fuels such as natural gas and diesel can be used not only in internal combustion engines but also in turbines. There are significant reserves of natural gas which will last for several decades [15]. This fuel is likely to dominate most cogeneration facilities in the next few decades, at least in Portugal, where there is a well-established distribution network. It is important to note that there are several cogeneration technologies that can use natural gas as fuel, such as gas turbines, micro-turbines, and Otto gas engines, among others.

2.6.2 Renewable fuels

Among the renewable fuels, biogas and biodiesel are most suitable for use in cogeneration processes [16]. Biogas is composed by a significant amount of methane and can be obtained from the gasification of woody and non-woody residues [15]. Biomass gasification for cogeneration is a promising technology that provides an excellent alternative to biomass combustion, especially in small-scale plants [14]. In addition, biodiesel can be produced from straight vegetable oil, animal oil/fats, tallow and waste cooking oil. The process used to convert these oils to biodiesel is called transesterification.

2.7 Technical and economic evaluation of cogeneration

The initial step in a project like this one is to identify the main issues and needs of the consumer so that the system can be designed with the highest efficiency. A practical advantage of cogeneration projects is their high flexibility and adaptability to each type of consumer.

The initial phase of this project is related to determining the energy needs of the installation, namely electric energy and thermal energy consumption. In addition, the costs related to the existing systems are also required. Subsequently, the ratio of heat to electricity has to be calculated, which corresponds to one of the main criteria for establishing a cogeneration system.

Then, it is necessary to design the installation that best suits the case study in terms of engines and/or turbines, electrical and thermal consumptions and other factors such as operation times as well as fuel availability and prices.

To make an economic analysis, a basic scenario of electric and thermal consumption needs to be defined. For this scenario, the costs associated with acquiring electric energy and with producing thermal energy separately and those under cogeneration conditions must be determined and compared. The added value of the cogeneration system, if any, should be compared to the additional investment that cogeneration demands. The price of electricity produced depends on both capital costs and primary fuel used, and also on the running costs of the installation and respective maintenance.

There are some economic indicators as well that have to be calculated in order to evaluate the profitability of the project. These indicators are payback time, which is the time from the initial investment to that point at which the cumulative returns become equal to the value of the initial investment, the Internal Rate of Return (IRR), which indicates when an investment can have zero return and the net present value (NPV), which is the present value of the project, calculated from future cash flows.

2.8 Environmental impact of cogeneration

Cogeneration is a very beneficial activity from an environmental point of view since most of the energy that a fuel can provide is efficiently used. Obviously this leads to a significant reduction in greenhouse gases emissions, as seen by comparing Figs. 11 and 12.

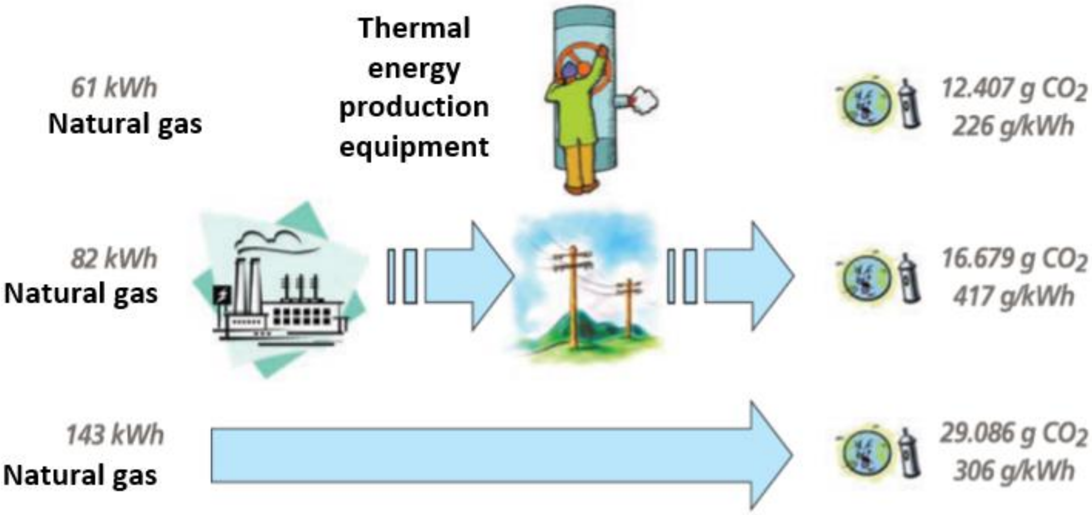


Fig. 11: Carbon dioxide emissions resulting from separate production of electric and thermal energies.

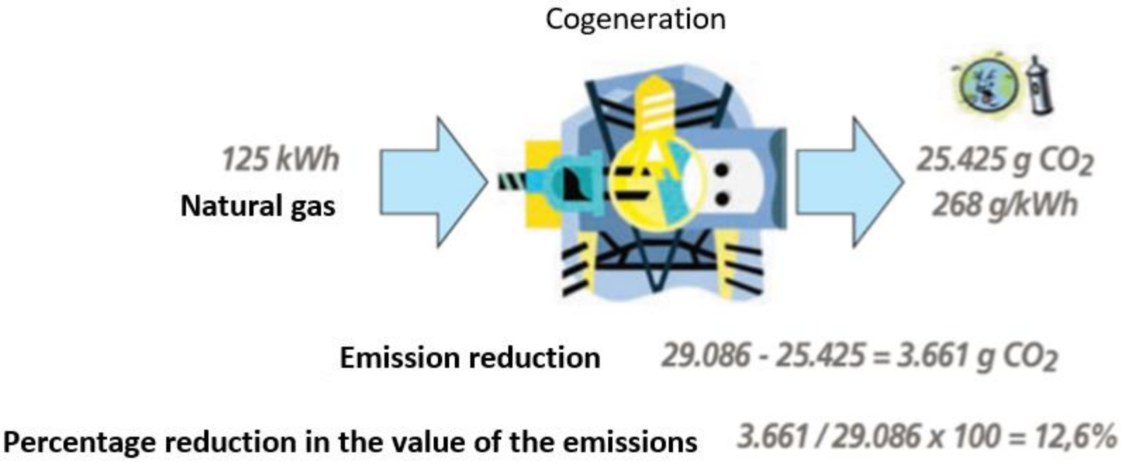


Fig. 12: Carbon dioxide emissions resulting from cogeneration of electric and thermal energies [1].

There is a reduction in CO2 emissions (12.6%) that is similar to the value of primary energy savings (12.59%).

Table 4 presents the pollutant limits established by Portuguese legislation for cogeneration units.

Particles		Mg/m3
Hydrocarbons	HC	50
Carbon Monoxide	CO	1000
Nitrogen oxides	NOx	450-1500*
Sulfur oxides	SO2	2700**

* 1500 power <10 MW and 450 power > 50 MW. Linear interpolation. Diesel engines emit 3,000 to 5,000. They require changes to be within the indicated limit values such as gas recirculation or retardation to ignition.

** It can be reached considering a fuel with 3.5% sulfur.

Table 4: Limits imposed by Portuguese legislation.

Within the European context, aiming at meeting the EU's binding goal of reducing by 2030 EU GHG emissions by at least 40% compared to 1990 was created the Directive (EU) 2018/410. This Directive identifies the CELE scheme as the main instrument to ensure GHG reduction targets, aiming at reducing the total amount of emissions permits. Installations included in National Implementation Measures (NIMs) are eligible for emissions permits free allocation. As all electricity producing facilities must be included in the NIMs, no emissions permits costs will be considered for this project as they will be allocated free of charge.

According to the Portuguese legislation, by Decree-Law No. 73/2010 was created the CIEC, Article 88 mentions the creation of the Tax on Petroleum and Energy Products. Article 89 mentions which are the exemptions for the case of cogeneration:

" Article 89 - Exemptions

1 - Exempt from the tax are petroleum and energy products which are proven to: (...)

d) Be used in electricity or electricity and heat (co-generation) production, (...)"

We may conclude therefore, since this project is a cogeneration plant, it will also be exempt from this tax.

On the other hand, in order to promote the transition towards a low carbon economy, a goal that has assumed great relevance at the national level, in line with the international context, the CO2 emission tax (commonly known as 'carbon tax') are created. According to Ordinance 384/2017 of 28 December, Article 2, the value of the CO2 emission tax is fixed at 6.85 € / ton of CO2, pursuant to Article 92 (3). - A of CIEC. The values of the addition on CO2 emissions to be applied to the products concerned are as follows:

	Addition Factor	Addition Amount
Gas	2.271654	€ 15.56/1000 l
Fuel, dyed and marked fuel	2.453658	€ 16.81/1000 l
Diesel, dyed and marked diesel and heating diesel	2.474862	€ 16.95/1000 l
GPL (methane and fuel gases)	2.902600	€ 19.88/1000 kg
Natural gas	0.056100	€ 0.38/GJ
Fuel oil	3.096000	€ 21.21/1000 kg
Pet coke	2.696100	€ 18.47/1000 kg
Coal and coke	2.265670	€ 15.52/1000 kg

Table 5: Values for carbon tax for each fuel.

2.9 Final considerations

The literature review on cogeneration technologies revealed that the emerging technologies are still under development, so these technologies were not considered in this study. On the contrary, conventional technologies are already well developed and established. Despite still being in the embryonic phase, emerging technologies still need to be looked at seriously in comparison with conventional forms. Nevertheless, since they are quite developed, solutions implementing conventional technologies were studied in this project. Among these technologies, gas turbines were also since they are used for electrical production above 5 MWe (in this study the electric output is 2 MWe. Steam turbines appear to be a good option for this project, given good efficiency and their possibility of using a primary fuel source, biomass, which is already used in the factory under study. Finally, internal combustion engines have excellent overall yields, so they will also be considered as a solution for the present project.

As for the primary energy to be used, the factory under study uses biomass as a source of thermal energy. Since its abundance in the region is high, it can be an excellent option not only to use with the steam turbine, but also to produce biogas to be used in the internal combustion engine. As for fossil fuels, natural gas is currently one of the most widely used fuels, originating much lower levels of CO2 emissions when compared to, for example, diesel. It is therefore a solution that is studied here.

3. Case study

3.1 Presentation of Pinewells

Pinewells is a wood pellet factory, relying on raw materials for manufacturing this product which are mainly leftovers, waste and forest by-products.

According to the selection of this raw material, Pinewells manufactures two types of product: "domestic" pellet and "industrial" pellets. The "domestic" pellet is manufactured with 100% peeled pine logs. This more demanding product is used in more sensitive equipment. Anything that is not suitable for “domestic” pellet manufacturing is used to make less demanding “industrial” pellets, which is used in large power plants and “district heating”.

Pinewells’ raw materials include all forest species, pine, eucalyptus, acacia, poplar, etc., which are mixed according to the needs of the product to be manufactured and in accordance with standards inherent in the pellet quality.

Pinewells' operating capacity is around 150,000 ton of pellets per year. However, the company’s effective capacity is around 132,000 ton of pellets per year, divided into 75% “industrial” and 25% “domestic” products.

Pinewells main markets are the national market and northern Europe, such as the UK, France and Denmark, for example.

3.2 Pellet production processes in Pinewells

The oldest form of energy is the use of wood as fuel, similar to how firewood is used.

Despite being a cheap product, at present many drawbacks exist, such as storage space, dirt, difficult transportation, dimensions, uncontrolled humidity, fire hazards and immediately uncontrolled temperature, etc.

Pellets are no more than wood pressed in a controlled manner into a suitable size so as to be useable in equipment that allows for maintaining a desired temperature within a desired time frame.

Pinewells' manufacturing process consists essentially of controlled wood processing according to the parameters of ISO 9001 and EN Plus. Dimensions, humidity, durability, heating value, handling and transportation, make up the essential parameters of these quality standards.

The process phases are then as follows:

At the entrance of the plant, the raw material is weighted and classified.

Afterwards, it is unloaded and packed for later use in suitable stacks, which are classified and numbered.

According to the different types of raw material available, the percentage of the mixed species to be used is defined according to the type of product the factory is going to manufacture.

According to the mix, the debarking and chipping line is fed with logs in order to obtain chips (in this phase up to ± 50mm in size)

Note: Bark and branches removed from the logs are used as biomass in our furnace producing the heat needed to dry the sawdust.

This product is led to a log separator, by size, from which we will obtain three sizes.

During the first separation and sawing, chips up to 15mm are produced, and these are led to the first "buffer" (silo 1).

During the second separation we get chips up to 50mm. this product will go through the hammer mills in order to turn it into a chip with an approximate size of 15mm, which is then also led to the first "buffer" (Silo 1).

Any product larger than 50mm is "rejected" and returns to the chipper.

The product in silo 1 is led to the dryer entrance, where it will be mixed with hot air from the furnace.

Once the bark has been removed and biomass acquired, we feed the furnace to produce the heat needed for the drying process.

The combustion/hot air product produced in the furnace, after being filtered and free of any suspended material, is placed into the dryer together with the chips that had been removed from the first buffer.

Afterwards, this mixture enters the dryer and remains there until most of the moisture is removed. The humidity of the chips at the inlet is around 45% whereas at the outlet it should be <10%. This control is carried out with the help of an infrared sensor at the dryer outlet. These "dry" chips are stored in the second buffer (Silo 2).

The grain size of the by-product suitable for manufacturing for example, by pressing, in order to obtain pellets must be <4mm. Therefore, if the "dry" chip we have still reaches 15mm, it is necessary to grind it again until the proper grain size is reached, which is to say, less than 4mm. The product after milling and dusting is sent to the third buffer (Silo 3).

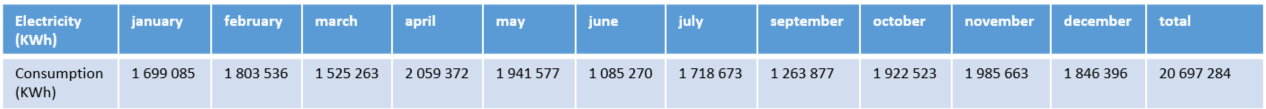
From the third buffer and under a controlled manner, the saw/chip with a maximum of 4mm is then conveyed to the presses to obtain the final pellet shape.

After the final product is pressed, it is cooled, sieved and dusted, and afterwards is sent to a storage silo where it can be shipped in bulk or sent to the bagging line. Appendix A.1 shows the complete current production process described in a flowchart.

3.3 Energy characterization of Pinewells

Pinewells is a factory that uses not only electrical energy but also thermal energy in its manufacturing process. The electrical energy comes from the grid and the thermal energy, used to dry the raw material, comes from a boiler that burns biomass residues.

Table 6 shows electrical consumption in 2018. The electricity consumed was about 2 GWh per month. The table reveals that the electric energy consumed varied between 1.085.270 kWh and 2.059.372 kWh.



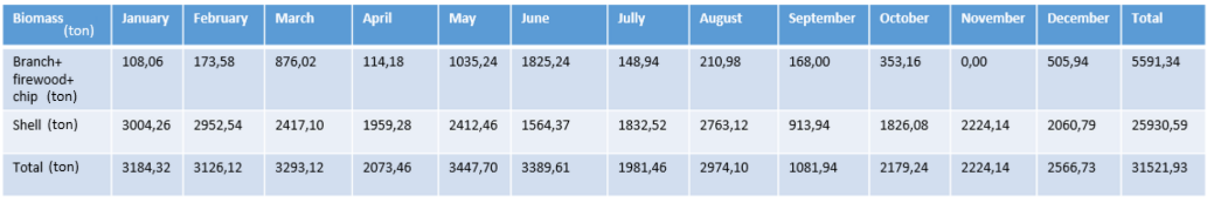
Electricity (KWh)	january	february	march	april	may	june	july	september	october	november	december	total
Consumption (KWh)	1 699 085	1 803 536	1 525 263	2 059 372	1 941 577	1 085 270	1 718 673	1 263 877	1 922 523	1 985 663	1 846 396	20 697 284

Table 6: Pinewells electrical consumption in 2018.

3.4 Use of biomass in Pinewells

As mentioned above, the thermal energy used in the manufacturing process comes from a boiler that burns biomass residues. This biomass comes not only from forest residues but also from bark and branches removed from the wood processed in the factory for pellet production.

Table 7 shows Pinewells' biomass consumption in 2018. As can be seen, the monthly biomass consumption in 2018 varied between 1.081.24 ton and 3.447.70 ton.



Biomass (ton)	January	February	March	April	May	June	Jully	August	September	October	November	December	Total
Branch+ firewood+ chip (ton)	108,06	173,58	876,02	114,18	1035,24	1825,24	148,94	210,98	168,00	353,16	0,00	505,94	5591,34
Shell (ton)	3004,26	2952,54	2417,10	1959,28	2412,46	1564,37	1832,52	2763,12	913,94	1826,08	2224,14	2060,79	25930,59
Total (ton)	3184,32	3126,12	3293,12	2073,46	3447,70	3389,61	1981,46	2974,10	1081,94	2179,24	2224,14	2566,73	31521,93

Table 7: Pinewells biomass consumption in 2018.

4. Proposed solution

4.1 Introduction

The study below considers the use of a steam turbine and an internal combustion engine for producing 2 MWe of electricity for consumption in the factory and 6.000 kW of thermal heat for consumption in a wood chip drying system.

Biomass and natural gas power plants are interesting solutions when there is need for thermal energy. Moreover, drying systems have a significant impact on the price and quality of the final product. Therefore, the combination of the two solutions appears to be promising for this project.

4.2 Methodology

The starting point for the project was the production of 2.000 kWe of electricity for self-consumption. Additional production of 8 ton/h of chips for use in a new dryer (band dryer) was also considered. The dryer that currently exists is a drum dryer although a band dryer would add more quality to the final product, as it dries the chips at lower temperature (in the order of 100 °C), avoiding the burning of the chips, thus becoming less dark and having more quality. Table 8 shows the technical characteristics of the new dryer.

Additional chip production	8 ton/h (output)
Humidity input	45%
Humidity output	6%
Type of dryer	Band dryer
Air temperature input	100º C
Air temperature output	40º C

Table 8: Technical characteristics of the new dryer.

An Excel sheet was made to calculate the necessary thermal powers, establishing the entire energy balance for each solution.

In the case of the steam turbine, Power Plant Simulator and Designer (PPSD) software was used. It is a modelling software that allows for determining energy balances of the system turbine/boiler.

In the case of the engines datasheets provided by the manufacturer were used to obtain the powers and energies necessary for making the calculations.

For the economic analysis, which was performed in an Excel sheet, an average price of 27 €/ton for the biomass, 0.023 €/kWh for the natural gas were considered and, in the case of electricity, the average prices considered are listed in Table 9.

	Average price of electricity €/kWh
Peak	0.119784
Off-peak	0.103838
Valley	0.074131
Super-valley	0.067315
Weighted average price	0.089907

Table 9: Average price of electricity.

Initially, Payback was used as an indicator for evaluation this project and this was divided by the investment required for each solution, in accordance with its result (EBITDA).

For calculating economic indicators that evaluate the profitability of the project, an Excel spreadsheet for each solution was created.

A table with the discount rate (inflation rate) of 1% at 20 years was made to increase the gains and costs of the project and, thus, the results of utilization. Operational cash flow was also indicated, which corresponds to EBITDA after subtracting taxes and amortizations, as well as the free cash flow of utilization, which corresponds to the amount of investment made (made in the first two years prior to utilization, years -1 and 0) with operational cash flow.

The economic indicators used where the IRR, which updates free cash flow of utilization to an discount rate of cash flows (WACC = 10% was considered), and the NPV which shows the value of the project in monetary terms, that is to say, what value this project could bring at the end of the 20 years projected.

The formulas used for calculation of IRR and NPV are automatic functions of Excel.

4.3 Solution using a steam turbine

4.3.1 Tailoring of the solution in the pellet manufacturing process

This solution includes the following main equipment:

- Boiler for producing steam and hot gases;
- Steam turbine with condensate extraction;
- Steam condenser;
- Exhaust steam air heater;
- Mixing chamber;
- Dryer.

The boiler has to produce hot gases in sufficient quantity and temperature to ensure a temperature of 100°C at the inlet of the band dryer. This dryer will receive the heat through a box that mixes the gases from the boiler with air heated by steam extraction. The air is further preheated by the turbine condensation circuit. Energy for drying is thus obtained without removing heat from the turbine.

Fig. 13 shows a schematic of this solution. A flowchart of the entire cogeneration system in the production process is shown in Appendix A.2.

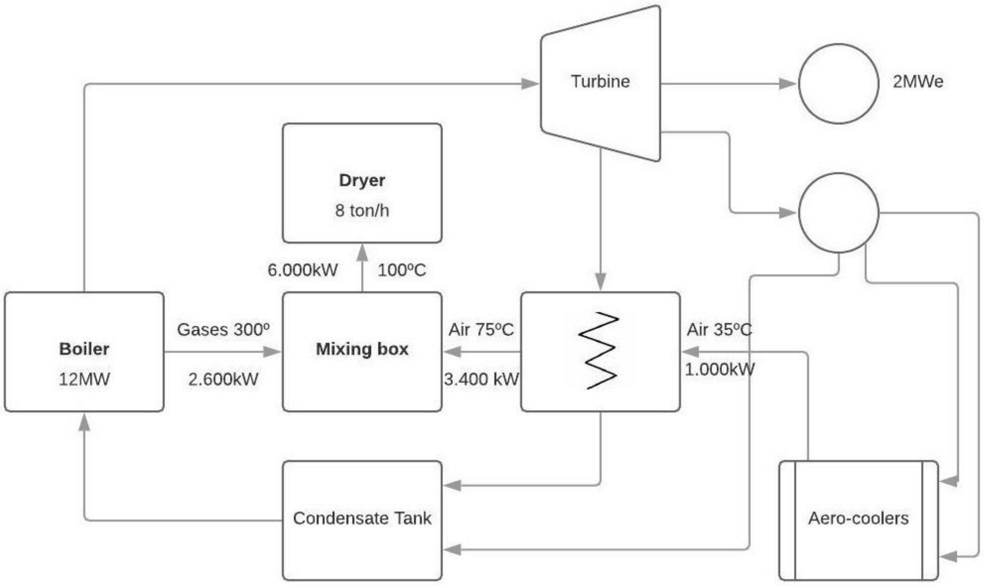


Fig. 13: Schematic of the solution using a steam turbine.

Currently, the biomass boiler generates heat, which in turn generates steam and hot gases that escape via the chimney. With this cogeneration project, steam and hot gases will be introduced as energy sources during the manufacturing process at Pinewells. Thus, the steam produced in the boiler will be used in a steam turbine to produce electricity for consumption within the factory. The hot gases will be used to supply 6,000 kW to the band dryer.

PPSD software was used to simulate the system in order to obtain more accurate values for thermal powers and temperatures to be used in the energy balance, as can be seen in Fig. 14.

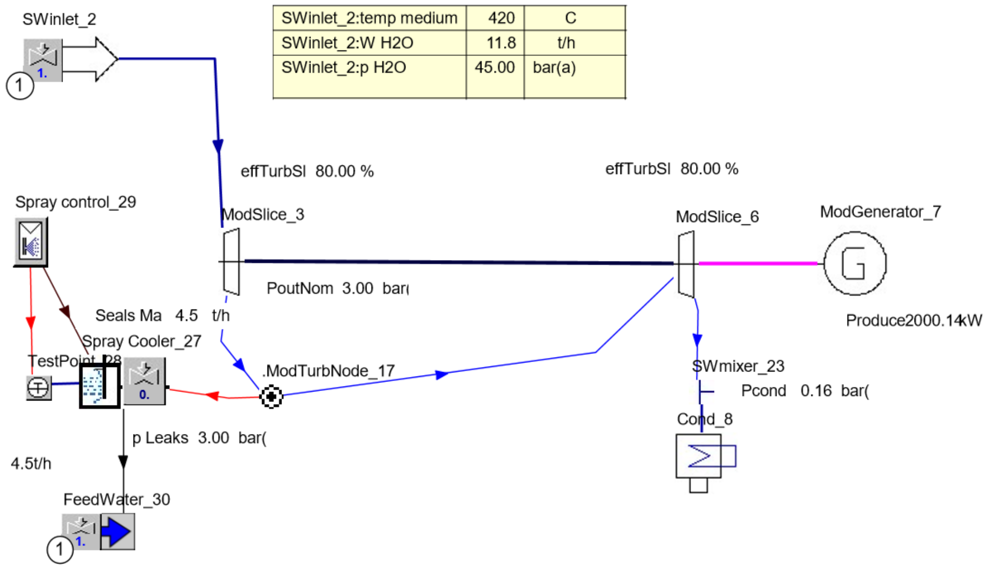


Fig. 14: Simulation using PPSD software.

4.3.2 Economic analysis and performance appraisal

Table 10 shows the data used for steam turbines.

Capacity of the steam turbine	2300 kW
Power losses	300 kW
Net power	2000 kW

Table 10: Technical characteristics of the steam turbine.

Table 11 shows the energy balance of this solution to obtain the consumption of biomass.

Energy to produce	2000 kWe (net power) and heat to dry 8 ton/h of chip
Energy input in the boiler (biomass)	12000 kW
Heat consumption in the current system, to dry the same amount of chips in the current system	5400 kW
Additional Energy consumption (biomass) to produce 2 MWe	6600 kW
Consumption of biomass	With an average PCI biomass of 2300 Kcal 2472 kg/h

Table 11: Energy balance of the solution using a steam turbine.

Table 12 shows the average price of electricity and Pinewells electrical consumption.

	Average price €/kWh	Consumption (kW h)
Peak	0.119784	191,565
Off-peak	0.103838	682,081
Valley	0.074131	502,117
Super-valley	0.067315	323,322
		1,699,085

Table 12: Average price of electricity and Pinewells electrical consumption.

Table 13 shows the calculations of the electricity consumed and its cost, energy savings due to the cogeneration system as well as the biomass consumption and its cost.

Consumption of electricity considering that the factory works 11 months a year, 30 days a month and 24 hours a day	
Weighted average price	0.089907 €/kW
Average daily consumption	56,636.17 kWh
Annual consumption	18,689,936.10 kWh
Annual cost	1,680,356.08 €/year
Energy savings calculation due to the 2,000 kWh produced by the Cogeneration system, considering that the factory works 11 months a year, 30 days a month and 24 hours a day	
Annual electricity production	15,840,000 kWh/year
Annual savings	1,424,126.88 €/year
Additional biomass cost considering that the factory works 11 months a year, 30 days a month and 24 hours a day	

Biomass consumption	2472 kg/h
Biomass price	27 €/ton
Annual biomass cost	528,612.48 €/year

Table 13: The electricity consumed and its cost, energy savings and the biomass consumption and its cost.

4.3.3 Feasibility study of the system included in an electric self-consumption regime

Estimated maintenance and operation costs are:

- Maintenance: € 2.53/h;
- Operation: € 1.18/h.

For producing electric energy the following equipment was considered:

- Boiler (500,000€);
- Turbine (3,000,000€);
- Water treatment system (200,000€);
- Auxiliary circuits (50,000€);
- Steam and condensate networks (500,000€);
- Air preheater (300,000€);
- Low voltage electrical installation (10,000€);
- Medium voltage electrical installation (100,000€).

The total investment is: € 4,660,000.

Table 14 shows the project results according to the number of working hours.

	3 Shifts **24h**	**2 Shifts** **16h**	**1 Shift** **8h**
Income (€)	1,424,126.00	949,417.92	474,708.67
Biomass costs (€)	-528,612.00	-352,408.32	-176,204.00
Natural gas costs (€)			
Maintenance (€)	-30,000.00	-13,333.33	-3,333.33
Operation (€)	-14,000.00	-6,222.22	-1,555.56
Result (EBITDA) (€)	**851,514.00**	**577,454.05**	**293,615.78**
Payback (years)	5.47	8.07	15.87
Investment (€)	4,660,000.00	4,660,000.00	4,660,000.00

Table 14: Project results according to the number of working hours.

For a more in-depth analysis of the profitability of the project, Table 15 shows the project results, NPV, IRR and payback. This table considers an discount rate of 1%, 2 shifts per day (16 hours), maintenance and operation costs varying according to the number of shifts, and a 20-year scenario for amortization of the investment. Table 15 is in Appendix B.1 with a larger scale.

Years	**-1**	**0**	**1**	**2**	**3**	**…**	**20**
Income (€)			949,418	958,912	968,501		1,147,000
Biomass costs (€)			-352,408	-355,932	-359,492		-425,748
Natural gas costs (€)			0	0	0		0
Maintenance (€)			-13,333	-13,467	-13,601		-16,108
Operation (€)			-6,222	-6,284	-6,347		-7,517
Result (EBITDA) (€)			**577,454**	**583,229**	**589,061**		**697,627**
Amortization (20 years) (€)			-233,000	-233,000	-233,000		-233,000
Result (EBIT) (€)			**344,454**	**350,229**	**356,061**		**464,627**
Tax IRC (22.5%) (€)			-77,502	-78,801	-80,114		-104,541
Amortization (20 years) (€)			233,000	233,000	233,000		233,000
Operational cash flow (€)	**0**	**0**	**499,952**	**504,427**	**508,947**		**593,086**
Investment in fixed asset (€)	-1,165,000	-3,495,000					
Total net investment (€)	**-1,165,000**	**-3,495,000**	**0**	**0**	**0**		**0**
Free cash flow exploration (€)	**-1,165,000**	**-3,495,000**	**499,952**	**504,427**	**508,947**		**593,086**

IRR	**9.2%**
NPV	**-214,495**
Payback	**8.07** **(8 years and 1 month)**

Table 15: Project results, NPV, IRR and Payback.

The criteria most sensitive to profitability are:

- Number of shifts:
    - 1 shift – 8 h;
    - 2 shifts – 4 h;
    - 2.5 shifts – 8 h;
    - 3 shifts – 24 h
- Price of biomass;
- Average cost of energy consumed by the network.
    - Varies according to whether consumption is during "peak", "off-peak", "valley" and "super-valley" periods.

The following sensitivity analysis was carried out combining the number of shifts with biomass price and the electricity purchase price:

Table 16 shows the sensitivity analysis combining the number of shifts with biomass price:

	Biomass price (€ / ton)					
Number of working hours (h)	Payback: 8.07	**23**	**25**	**27**	**29**	**31**
	8	30.07	36.17	45.35	60.8	92.21
	16	7.40	7.72	**8.07**	8.45	8.87
	20	5.37	5.54	5.72	5.91	6.11
	24	4.22	4.32	4.43	4.54	4.66

Table 16: Sensitivity analysis combining the number of shifts with biomass price.

Analyzing the table and considering the price of biomass at 27 €/ton and 2 shifts per day (16h) as a base scenario, the payback is 8 years and 1 month. It can be concluded that as the price of biomass increases, payback also increases; however, the number of shifts performed seems to have a greater impact on payback. For example, at a cost of 30 €/ton of biomass, maintaining 2 shifts, payback period increases to 8 years and 8 months. On the other hand, if the number of shifts increases, keeping the biomass price at 27 €/ton, the payback will be reduced to 4 years and 5 months.

Table 17 shows the sensitivity analysis combining the number of shifts with the electricity purchase price:

	Price of electricity (€ / kWh)					
Number of working hours (h)	Payback: 8.07	**0.081907**	**0.085907**	**0.089907**	**0.103838**	**0.119784**
	8	77.02	57.09	45.35	26.43	17.89
	16	9.45	8.71	**8.07**	6.43	5.22
	20	6.57	6.12	5.72	4.67	3.85
	24	5.04	4.71	4.43	3.66	3.05

Table 17: Sensitivity analysis combining the number of shifts with the energy price.

Looking at the table, considering, the electricity price of 0.089907 €/kWh and 2 work shifts per day (16h) as a base scenario, the payback is 8 years and 1 month. The base energy price was estimated based on the January 2018 invoice. However, on April, May, June and July invoices, this weighted average price falls to 0.0863829 €/kWh, which is why this variation was taken into consideration for this sensitivity analysis. That is to say, energy prices have a greater impact on this project than the cost of biomass, improving payback the more the cost of electricity increases and vice versa. For example, at a cost of 0.081907 €/kWh, maintaining the two shifts, Payback increases to almost 9 years and 6 months.

4.3.4 Impact of decarbonization policies

As discussed in chapter 2.8, the fact that this project concerns a cogeneration plant allows the emission permit to be obtained, free of charge, as well as the Petroleum and Energy Products Tax (ISP) requires no payment.

On the other hand, since this solution uses biomass as fuel, i.e. renewable energy, it is exempt from the carbon tax, despite the fact that when the energy stored in biomass is burned, greenhouse gases, in particular carbon dioxide (CO2) are emitted.

However, this amount of CO2 is lower than that consumed in the production of photosynthesis. Thus, the use of biomass as fuel generates a small net reduction of CO2 into the atmosphere. If biomass is not burned, its natural decomposition would give rise to the same amount of CO2. If biomass is used in energy production, it also contributes to reducing the use of fossil fuels by avoiding CO2 emissions. This is the main reason why CO2 emissions from burning biomass are not taxed.

4.4 Solution using a natural gas-fired internal combustion engine

4.4.1 Tailoring of the solution in the pellet manufacturing process

This solution includes the following main equipment:

- System Support Boiler;
- Internal combustion engine;
- Air cooler with engine cooling water;
- Mixing chamber;
- Dryer.

The engine is sized to suit the electrical needs of the factory, taking advantage of the power of the engine exhaust and cooling circuit to be used in the band dryer. Exhaust gases will be sent through a mixing chamber that also receives the air heated from engine cooling circuits. In this chamber, 100ºC will be guaranteed. However, as will be studied, the thermal energy supplied by the engine will not be sufficient for the dryer; therefore additional heat needs to be guaranteed by an external system, which, in this case, a biomass boiler was considered.

Fig. 13, showing a flowchart of the entire cogeneration system in the production process, is shown in Appendix A.3.

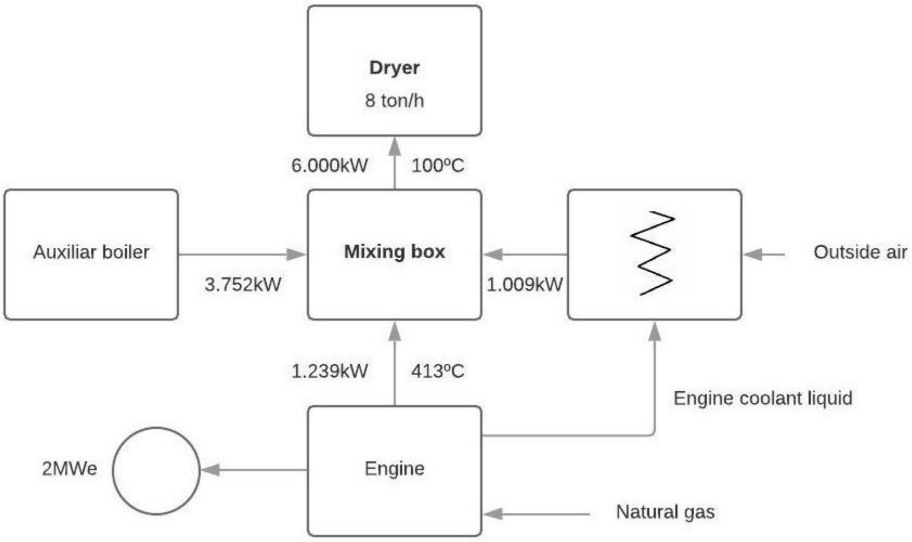


Fig. 15: Cogeneration solution flowchart using a natural gas-fired internal combustion engine.

4.4.2 Economic analysis and performance appraisal

Table 18 shows the data used for the natural gas engine.

Capacity of the engine	2000 kW
Power losses	60 kW
Net power	1940 kW

Table 18: Technical characteristics of the natural gas engine.

Table 19 shows the energy balance of this solution to obtain thermal power offered by the engine and biomass consumption.

Energy to produce	2000 kWe (net power) and heat to dry 8 ton/h of chips
Energy input in the dryer	6000 kW
Thermal power from engine gases and cooling circuit (per engine datasheet)	
Exhaust gas heat	10871 kg/h
Exhaust gas temperature	413 ºC
Heat from engine gases	$Q = m \times dT \times Cp$ $heat = mass\ flow \times temperature\ difference \times specific\ heat\ capacity$ $Q = \frac{10871}{3600} \times (413 - 40) \times 1{,}1 = 1239$ kW (1)
Heat from engine cooling circuit	1009 kW
Total thermal power from engine	2248 kW
Additional energy consumption (biomass)	
Additional consumption	3752 kW

Table 19: Energy balance of the solution using natural gas-fired internal combustion engine.

Table 20 shows the calculations of energy savings due to the cogeneration system as well as biomass and natural gas consumption and their costs.

<table>
<tr><td colspan="2">Since the electrical energy produced is the same, annual energy savings is the same as the previous solution</td></tr>
<tr><td>Annual savings</td><td>1,424,126.88 €/year</td></tr>
<tr><td colspan="2">For this cogeneration solution there are two costs, the cost of natural gas and the cost of additional biomass. Cost of natural gas considering that the factory works 11 months a year, 30 days a month and 24 hours a day:</td></tr>
<tr><td>Natural gas consumption of the engine (per engine datasheet)</td><td>4579 kWh</td></tr>
<tr><td>Cost of natural gas (based on natural gas price of August 2019)</td><td>0.023 €/kWh</td></tr>
<tr><td>Total cost of natural gas per year</td><td>834,110.64 €/year</td></tr>
<tr><td colspan="2">Additional biomass cost considering that the factory works 11 months a year, 30 days a month and 24 hours a day</td></tr>
<tr><td>Biomass consumption</td><td>1478 kg/h</td></tr>
<tr><td>Biomass price</td><td>27 €/ton</td></tr>
<tr><td>Annual biomass costs</td><td>316,055.52€/year</td></tr>
<tr><td colspan="2">Total cost of natural gas and biomass</td></tr>
<tr><td>Total cost</td><td>1,149,254 €/year</td></tr>
<tr><td colspan="2">At this value the cost of the biomass that in the current system would dry the same amount of chip can be removed. This value enters as a benefit in the calculations</td></tr>
</table>

Power of biomass in the current system to dry the same amount of chip	5400 kW
Biomass consumption	2022 kg/h
Biomass price	27 €/ ton
Annual biomass costs	432,384 €/year
Total cost of natural gas and final biomass	716,870 €/year

Table 20: Electricity consumed and its cost, energy savings and the biomass consumption and its cost.

4.4.3 Feasibility study of the system included in an electric self-consumption regime

Estimated maintenance and operation costs are:

- Maintenance: € 15/h
- Operation: € 3.80/h

For producing electric energy the following equipment was considered:

- Boiler (250,000€);
- Internal combustion engine (800,000€);
- Water treatment system (10,000€);
- Auxiliary circuits (30,000€);
- Gas lines (50,000€);
- Low voltage electrical installation (10,000€);
- Medium voltage electrical installation (50,000€).

The total investment is: € 1,200,000.00

Table 21 shows the project results according to the number of working hours.

	3 Shifts **24h**	**2 Shifts** **16h**	**1 Shift** **8h**
Income (€)	1,856,511.36	1,381,802.40	907,093.44
Biomass costs (€)	-316,055.52	-210,703.68	-105,351.84
Natural gas costs (€)	-834,110.64	-556,073.76	-278,036.88
Maintenance (€)	-118,800.00	-79,200.00	-39,600.00
Operation (€)	-30,096.00	-20,064.00	-10,032.00
Result (EBITDA) (€)	**557,559.20**	**515,760.96**	**474,072.72**
Payback (years)	2.15	2.33	2.53
Investment (€)	1,200,000.00	1,200,000.00	1,200,000.00

Table 21: Project results according to the number of working hours.

For a more in-depth analysis of the profitability of the project, Table 22 shows the project results, NPV, IRR and Payback. This table considered an discount rate of 1%, 2 shifts per day (16 hours), maintenance and operation costs varying according to the number of shifts, and a 20-year scenario for amortization of investment. Table 17 is in Appendix B.2 on a larger scale.

Years	**-1**	**0**	**1**	**2**	**3**	**…**	**20**
Income (€)			1,381,802	1,395,620	1,409,577		1,669,368
Biomass costs (€)			-210,704	-212,811	-214,939		-254,553
Natural gas costs (€)			-556,074	-561,634	-567,251		-671,798
Maintenance (€)			-79,200	-79,992	-80,792		-95,682
Operation (€)			-20,064	-20,265	-20,467		-24,239
Result (EBITDA) (€)			**515,761**	**520,919**	**526,128**		**623,095**
Amortization (20 years) (€)			-60,000	-60,000	-60,000		-60,000
Result (EBIT) (€)			**455,761**	**460,919**	**466,128**		**563,095**
Tax IRC (22.5%) (€)			-102,546	-103,707	-104,879		-126,696
Amortization (20 years) (€)			60,000	60,000	60,000		60,000
Operational cash flow (€)	**0**	**0**	**413,215**	**417,212**	**412,249**		**496,399**
Investment in fixed assets (€)	-300,000	-900,000					
Total net investment (€)	-300,000	-900,000	0	0	0		0
Free cash flow exploration (€)	**-300,000**	**-900,000**	**413,215**	**417,212**	**412,249**		**496,399**

IRR	**32.7%**
NPV	**2,083,205**
Payback	**2.33** **(2 years and 4 months)**

Table 22: Project results, NPV, IRR and Payback.

The criteria most sensitive to profitability are:

- Number of shifts that the company works:
    - 1 shift - 8h;
    - 2 shifts – 4h;
    - 2.5 shifts – 8h;
    - 3 shifts - 24h
- Price of biomass;
- Price of natural gas;
- Average cost of energy consumed by the network;
    - Varies according to whether consumption is during "peak", "off-peak", "valley" and "super-valley" periods.

The following sensitivity analysis was performed by combining the number of shifts with the price of biomass, energy purchase costs and natural gas costs:

Table 23 shows the sensitivity analysis combining the number of shifts with the price of biomass:

	Biomass price (€ / ton)					
Number of working hours (h)	Payback: 2.33	**23**	**25**	**27**	**29**	**31**
	8	2.82	2.67	2.53	2.41	2.30
	16	2.48	2.40	**2.33**	2.25	2.19
	20	2.35	2.29	2.24	2.19	2.14
	24	2.22	2.19	2.15	2.12	2.09

Table 23: Sensitivity analysis combining the number of shifts with the biomass price.

According to the table analysis, for the base scenario, the price of biomass of 27 €/ ton and two shifts (16h), meaning that Payback is in 2 years and 4 months. It can be observed that as the price of biomass increases, Payback decreases. However, the number of shifts working seems to have a greater impact on return on investment. For example, at a cost of 31 €/ ton of biomass, maintaining 2 shifts, Payback decreases to 2 years and 2 months. If the number of shifts increases, keeping the price of biomass at 27 € / ton, Payback decreases to 2 year and 1 months.

Table 24 shows the sensitivity analysis combining the number of shifts with the electricity purchase price:

	Price of electricity (€ / kWh)					
Number of working hours (h)	Payback: 2.33	**0.081907**	**0.085907**	**0.089907**	**0.103838**	**0.119784**
	8	2.78	2.65	2.53	2.19	1.90
	16	2.78	2.53	**2.33**	1.81	1.44
	20	2.78	2.48	2.24	1.67	1.29
	24	2.79	2.43	2.15	1.54	1.16

Table 24: Sensitivity analysis combining the number of shifts with the electricity purchase price.

As can be seen from this sensitivity analysis, for the electricity price of 0.089907 €/kWh and 2 shifts (16h), the payback is 2 years and 4 months. The base energy price was estimated based on the January 2018 invoice. However, on April, May, June and July invoices, this weighted average price falls to an estimated 0.0863829 €/kWh, which is why this variation was taken into consideration for this sensitivity analysis. Hence, the electricity purchase has a greater impact than the cost of biomass in this project, lowering the payback, the greater the cost of electricity increases and vice versa. For example, with a cost of 0.119784 €/ kWh, maintaining 2 shifts, Payback decreases to 1 years and 5 months.

Table 25 shows the sensitivity analysis combining the number of shifts with the purchase price of natural gas:

	Price of natural gas (€ / kWh)					
Number of working hours (h)	Payback: 2.33	**0.020435202**	**0.021679706**	**0.023**	**0.0244007**	**0.025886703**
	8	2.38	2.45	2.53	2.63	2.73
	16	2.08	2.19	**2.33**	2.49	2.69
	20	1.95	2.01	2.24	2.43	2.67
	24	1.84	1.98	2.15	2.37	2.65

Table 25: Sensitivity analysis combining the number of shifts with the purchase price of natural gas.

Observing the table, we can conclude that for the base scenario, the natural gas price of 0.023 €/kWh and 2 shifts (16h) working each day, the payback is 2 years and 4 months. As the price of natural gas increases, the payback also increases. However, the number of shifts performed seems to have a greater impact on return on investment. For example, at a cost of 0.025886703 €/kWh of natural gas, maintaining 2 shifts, Payback increases to almost 3 years. If the number of shifts increases, keeping the price of natural gas at 0.023 €/kWh, Payback decreases to 2 year and 1 month.

4.4.4 Impact of decarbonization policies

As discussed in chapter 2.8, the fact that this project concerns a cogeneration plant allows the emission permit to be obtained, free of charge, as well as the Petroleum and Energy Products Tax (ISP) requires no payment.

However, as a solution using natural gas, it has to pay the carbon tax. According to Table 5, the natural gas addition factor is 0.056100 over the value of 6.85 € / ton CO2, which equals 0.38 € / GJ.

Since the natural gas consumption for the chosen engine is 4579 kWh (converting to GJ equals 16.4844GJ) after one year (assuming the plant works 11 months a year, 30 days a month and 16 hours per day), the consumption is 87,037,632 GJ. This corresponds to an amount of € 33,074.30 after one year.

To carry out an analysis of the impact that this rate may have on the payback of this project we will use the values that were calculated for the situation of 2 working shifts per day. By subtracting the carbon value payable from the economic result, the payback increases to 2.57 years.

Although it does not have a large impact on the payback for these rate values, the impact may be greater if this rate is increased, which is a very likely assumption given the efforts being made worldwide to fight the carbon emissions into the atmosphere.

4.5 Solution using a biogas-fired internal combustion engine

4.5.1 Tailoring of the solution in the pellet manufacturing process

This solution includes the following main equipment:

- System Support Boiler;
- Biomass Gasifier;
- Internal combustion engine;
- Steam condenser;
- Air cooler with engine cooling water;
- Mixing chamber;
- Dryer.

The size of the engine is according to the electrical need of the factory. In addition, a normal natural gas engine cannot be used; the engine concerned has to work with biogas as fuel. The engine supplier indicated how much biogas the engine needs to consume in order to produce the desired electrical power. With this value, the biomass gasifier supplier sized the equipment and indicated the amount of biomass the gasifier needs to consume to produce the amount of biogas required by the engine supplier. The exhaust gas energy and the engine cooling circuit are used in the band dryer. Exhaust gases will be sent through a mixing chamber which also receives heated air from engine cooling circuits. In this chamber 100ºC will be guaranteed.

However, as will be studied, the thermal energy supplied by the engine will not be sufficient for the dryer, therefore additional heat needs to be guaranteed by an external system, so in this case a biomass boiler was considered.

Fig. 13 shows a schematic of this solution. A flowchart of the entire cogeneration system in the production process is shown in Appendix A.4.

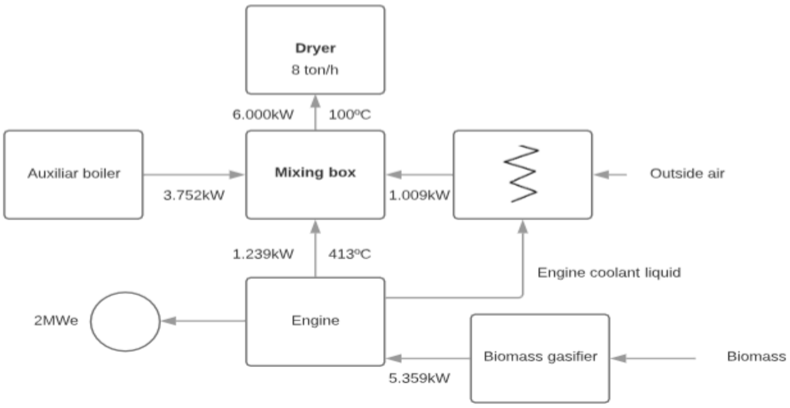


Fig. 16: Cogeneration solution flowchart using a biogas-fired internal combustion engine.

4.5.2 Economic analysis and performance appraisal

Table 26 shows the data used for this gas engine. It is a biogas-fired version of the same engine model considered in the previous solution.

Capacity of the engine	2000 kW
Power losses	60 kW
Net power	1940 kW

Table 26: Technical characteristics of the engine.

Table 27 shows the energy balance of this solution to obtain thermal power offered by the engine and biomass consumption.

Energy to produce	2000 kWe (net power) and heat to dry 8 ton/h of chip
Energy input in the dryer	6000 kW
Thermal power from engine gases and cooling circuit (per engine datasheet)	

Exhaust gas heat	10258 kg/h
Exhaust gas temperature	390ºC
Heat from engine gases	$Q = m\ dT \times Cp$ $heat = mass\ flow \times temperature\ difference \times specific\ heat\ capacity$ $Q = \frac{10258}{3600} \times (390 - 40) \times 1{,}1 = 1097$ kW (2)
Heat from engine cooling circuit	989 kW
Total thermal power from engine	2086 kW
Additional energy consumption (biomass)	
Additional consumption	3914 kW

Table 27: Energy balance of the solution using biogas-fired internal combustion engine.

According to the datasheet provided by the engine supplier, biogas consumption is 5359 kWh. Given this value, the gasifier will be developed by the supplier specifically for this project so that its output is almost the same as the engine's fuel input.

According to the supplier, for this biogas production value, the gasifier consumes 2008 kg / h of biomass.

Table 28 shows the calculations of energy savings due to the cogeneration system as well as biomass consumption and its cost.

Since the electrical energy produced is the same, annual energy savings is the same as the previous solution	
Annual savings	1,424,126.88 €/year
For this cogeneration solution, two costs will be considered, the cost of biomass for the Gasifier and the cost of additional biomass. These two costs will be calculated considering that the factory works 11 months a year, 30 days a month and 24 hours a day. Cost of biomass for Gasifier:	
Biomass consumption	2008 kg/h

Biomass price	27 €/ ton
Annual biomass costs	429,390.72 €/ year
Additional biomass for the production of thermal energy, considering that the factory works 11 months a year, 30 days a month and 24 hours a day	
Biomass consumption	1542 kg/h
Price of biomass	27 €/ton
Annual biomass costs	329,741.28 €/year
Total cost of biomass	
Total cost	759,132 €/year
At this value the cost of the biomass that in the current system would dry the same amount of chip can be removed. This value enters as a benefit in the calculations	
Power of biomass in the current system to dry the same amount of chip	5400 kW
Biomass consumption	2022 kg/h
Biomass price	27 €/ ton
Annual biomass cost	432,384 €/year
Total cost of biomass	326,748 €/year

Table 28: Electricity consumed and its cost, energy savings and biomass consumption and its cost.

4.5.3 Feasibility study of the system included in an electric self-consumption regime

The estimated maintenance and operation costs are:

- Maintenance: 32 €/h;
- Operation: 7.90 €/h.

For producing electric energy the following equipment was considered:

- Boiler (250,000€);
- Internal combustion engine (1,000,000€);
- Biomass Gasifier (2,150,000€);
- Water treatment system (10,000€);
- Auxiliary circuits (30,000€);
- Low voltage electrical installation (10,000€);
- Medium voltage electrical installation (50,000€).

The investment is: 3,500,000.00 €

Table 29 shows the project results according to the number of working hours.

	3 Shifts **24h**	**2 Shifts** **16h**	**1 Shift** **8h**
Income (€)	1,856,511.36	1,381,802.40	907,093.44
Biomass costs (€)	-759,132.00	-506,088.00	-253,044.00
Natural gas costs (€)	0	0	0
Maintenance (€)	-253,440.00	-168,960.00	-84,480.00
Operation (€)	-62,568.00	-41,712.00	-20,856.00
Result (EBITDA) (€)	**781,371.36**	**665,042.40**	**548,713.44**
Payback (years)	4.48	5.26	6.38
Investment (€)	3,500,000.00	3,500,000.00	3,500,000.00

Table 29: Project results according to the number of working hours.

For a more in-depth analysis of the profitability of the project, Table 30 shows the project results, NPV, IRR and Payback. This table considered an discount rate of 1%, 2 shifts per day (16 hours), maintenance and operation costs varying according to the number of shifts, and a 20-year scenario for amortization of investment. Table 30 is in the Appendix B.3 on a larger scale.

Years	-1	0	1	2	3	…	20
Income (€)			1,381,802	1,395,620	1,409,577		1,669,368
Biomass costs (€)			-506,088	-511,149	-516,260		-611,409
Natural gas costs (€)			0	0	0		0
Maintenance (€)			-168,960	-170,650	-172,356		-204,122
Operation (€)			-41,712	-42,129	-42,550		-50,393
Result (EBITDA) (€)			**665,042**	**671,693**	**678,410**		**803,444**
Amortization (20 years) (€)			-175,000	-175,000	-175,000		-175,000
Result (EBIT) (€)			**490,042**	**496,693**	**503,410**		**628,444**
Tax IRC (22.5%) (€)			-110,260	-111,756	-113,267		-141,400
Amortization (20 years) (€)			175,000	175,000	175,000		175,000
Operational cash flow (€)	**0**	**0**	**554,783**	**559,937**	**565,143**		**662,044**
Investment in fixed asset (€)	-875,000	-2,625,000					
Total net investment (€)	**-875,000**	**-2,625,000**	**0**	**0**	**0**		**0**
Free cash flow exploration (€)	**-875,000**	**-2,625,000**	**554,783**	**559,937**	**565,143**		**662,044**

IRR	**15.1%**
NPV	**1,186,607**
Payback	**5.26** **(5 years and 3 months)**

Table 30: Project results, NPV, IRR and Payback.

The criteria most sensitive to profitability are:

- Number of shifts that the company works:
  - 1 shift - 8h;
  - 2 shifts – 4h;
  - 2.5 shifts – 8h;
  - 3 shifts - 24h.
- Price of biomass;
- Average cost of energy consumed by the network;
  - Varies according to whether consumption is during "peak", "off-peak", "valley" and "super-valley" periods.
  - The following sensitivity analysis was carried out combining the number of shifts with the biomass price and the energy purchase price.

Table 31 shows the sensitivity analysis combining the number of shifts with the price of biomass:

	Biomass price (€ / ton)					
Number of working hours (h)	Payback: 5.26	**23**	**25**	**27**	**29**	**31**
	8	6.70	6.54	6.38	6.23	6.08
	16	5.18	5.22	**5.26**	5.31	5.35
	20	4.65	4.74	4.84	4.94	5.05
	24	4.22	4.34	4.48	4.62	4.78

Table 31: Sensitivity analysis combining the number of shifts with the price of biomass.

Analyzing the table and considering as a base scenario, the price of biomass 27 €/ ton and 2 shifts per day (16h), the payback is 5 years and 3 months. It can be concluded that as the price of biomass increases, payback increases, however, the number of shifts performed seems to have a greater impact on return. For example, at a cost of 31 €/ ton of biomass, maintaining 2 shifts, Payback increases to 5 years and 4 months. On the other hand, if the number of shifts increases, keeping the biomass price at 27 €/ ton, the payback decreases to 4 years and 5 months.

Table 32 shows the sensitivity analysis combining the number of shifts with electricity purchase price:

		Price of electricity (€ / kWh)				
Number of working hours (h)	Payback: 5.26	**0.081907**	**0.085907**	**0.089907**	**0.103838**	**0.119784**
	8	6.91	6.63	6.38	5.62	4.95
	16	6.03	5.62	**5.26**	4.31	3.57
	20	5.67	5.22	4.84	3.86	3.13
	24	5.35	4.87	4.48	3.49	2.79

Table 32: Sensitivity analysis combining the number of shifts with electricity purchase price.

As can be seen from this sensitivity analysis, for electricity prices of 0.089907 €/ kWh and 2 shifts (16h), the payback is 5 years and 3 months. The base energy price was estimated based on the January 2018 invoice. However, on April, May, June and July invoices, this weighted average price falls to 0.0863829 €/ kWh, which is why this variation was taken into consideration in this sensitivity analysis. As a result, electricity purchase price has a greater impact than the cost of biomass in this project, as the more the cost of electricity increases, payback decreases and vice versa. For example, with a cost of 0.119784 €/ kWh, maintaining 2 shifts, Payback decreases to 3 years and 7 months.

4.5.4 Impact of decarbonization policies

As discussed in chapter 2.8, the fact that this project concerns a cogeneration plant allows the emission permit to be obtained, free of charge, as well as the Petroleum and Energy Products Tax (ISP) requires no payment.

On the other hand, since this solution uses biogas (transformed from biomass) as fuel, which is to say renewable energy, it is exempt from the carbon tax, despite the fact that when biogas is burned, greenhouse gases are emitted, in particular carbon dioxide (CO2).

However, encouraging the development of fuels through renewable energy is the main reason why CO2 emissions from biogas burning are not taxed.

5. Analysis and discussion of the solutions

5.1 Technical analysis

To carry out a technical analysis, it is necessary to compare the components that are required for each of the solutions and see how they fit into the production process, as well as the yields of cogeneration technologies to be used and the quality of the end product.

Looking at Table 2, we can conclude that the two technologies used in each of the solutions have very similar yields.

Regarding the components required for the solutions to fit into the factory production process, there is cross-sectional equipment common to three solutions, since they are necessary to ensure that the thermal energy is optimal at the dryer inlet. For the first solution the use of a steam turbine, a boiler, as well as air coolers, condensation tanks and mixing boxes was considered. In the case of the solution using the natural gas engine, in addition to the engine, it is necessary to add a mixing box and a boiler to meet thermal energy needs. In the case of the solution described in 4.5, all components of the solution in 4.4 are used, adding the biomass gasifier.

As for the quality of the final product, it is the same for any solution, because in all three cases the system is prepared so that the air intake in the dryer is ideal for operation. If we compare the product quality at present, the quality is superior. As mentioned before, it is a band dryer that allows for obtaining a better quality final product than the current dryer. In conclusion, from a technical point of view, all solutions are very competitive for this project.

5.2 Economical analysis

In order to make an economic comparison of the solutions studied, the economic indicators generated in the Excel sheets will be taken into account. More important than the investment required for each case, it is important to analyze return on investment, IRR and NPV to assess whether the investment is profitable and how long it is recoverable.

In the case of the steam turbine, with an investment of € 4,600,000, it has a payback of 8 years and 1 month, an IRR of 9.2% and an NPV of € -214,495. This means that after 8 years and 1 month the investment can be recovered, however, the assessment of this investment is negative, i.e. the calculation of future cash flows is not capable of generating positive financial flows. In a way, the fact that profitability is so low further emphasizes this statement. A very low IRR means there are better investments and alternative projects.

In the case of the natural gas internal combustion engine solution, the € 1,200,000 investment can be recovered in 2 years and 4 months. In addition, with future cash flows updated, we still have an assessment of € 2,083,205 (NPV), which is much more attractive than the previous situation. The nearly 32.7% IRR supports this conclusion as it is quite high for the average of this type of project.

Finally, regarding the solution presented in 4.5, the € 3,500,000 investment is recoverable in 5 years and 3 months. With a good value of NPV (1,186,607 €) and the IRR reaches 15.1%, the project is very attractive as the solution presented in 4.4. It is a more favorable option than 4.3, as it has a payback of almost 5 years, with an investment between the two previous solutions.

In short, the solution using a natural gas engine is the most attractive, followed by the solution using a biogas gasifier and finally the solution using a steam turbine.

5.3 Environmental analysis

Overall, cogeneration has a positive environmental impact when compared to separate production of electrical and thermal energy.

For NOx emissions into the atmosphere, the steam turbine has slightly higher emissions than internal combustion engines. 0.9 kg / MWh and 0.5 kg / MWh, respectively.

From the point of view of CO2 emissions, when energy stored in biomass is burned, greenhouse gases are emitted, in particular carbon dioxide (CO2). However, this amount of CO2 is lower than that consumed in photosynthesis biomass production. Thus, the use of biomass as fuel generates a small net reduction of CO2 into the atmosphere. If biomass is not burned, its natural decomposition would give rise to the same amount of CO2. If biomass is used in energy production, it also contributes to reducing fossil fuel use and in turn, lowers overall CO2 emissions.

As studied for each solution, these CO2 emissions are only taxed for the solution where natural gas is the fuel (solution discussed in 4.4). Where these rates may even change economic indicators substantially, as the carbon rate tends to increase as a result of decarbonization policies adopted around the world.

In conclusion, from the environmental point of view, the solutions that uses biomass as a primary energy source is more advantageous than the solution that uses natural gas.

6. Final summary

6.1 Conclusions

From this work, it was concluded that, in general, there are advantages to using cogeneration processes when there is available use of thermal and electrical energy. However, the cost-effectiveness of the project varies depending on the cogeneration technology to be used, as well as the primary energy source.

As studied, there are other factors that may influence project profitability, such as the price of biomass, the price of electricity, the number of shifts/working hours of the factory and the price of natural gas.

The choice of the most suitable solution varies according to the owner's criteria.

However, given that this is a project aiming at the future, the impact that decarbonization policies may have on this project must be taken into account. Increasingly, GHG emissions are the subject of discussion in major world scenarios, and measures have been taken to tax these emissions increasingly.

In conclusion, and given the reasons presented in the previous paragraph, the solution using natural gas as the primary source of energy should be discarded. Regarding solutions with biomass as the primary energy source, the solution using the biogas engine should be chosen because the economic indicators are much more positive when compared to the solution using the steam turbine.

6.2 Future work

Regarding issues for future work, within the solutions studied, using conventional technologies, it is suggested that exploiting biogas, which at this moment, in Portugal, still does not bring great advantages, but in the near future, new legislation for biogas sales for the distribution network, as is already the case in other European countries, could be studied, as well as producing biogas for car fuel or for sale to external customers.

Within the area of biomass, other processes for turning solid biomass into fuels that are able to be used in cogeneration, for example pyrolysis, can also be researched.

On the other hand, despite still being in an embryonic state at the moment and not having great advantages in their use, mainly due to very high investment costs, emerging technologies are a good solution for the future. Therefore, they may be considered in this same project at a future opportunity.

Finally, research can also be carried out to increase the electrical capacity produced so that, in addition to self-consumption at the factory, it can also be sold to the network. However, the study must be careful due to large fluctuations in rates for buying and selling electricity.

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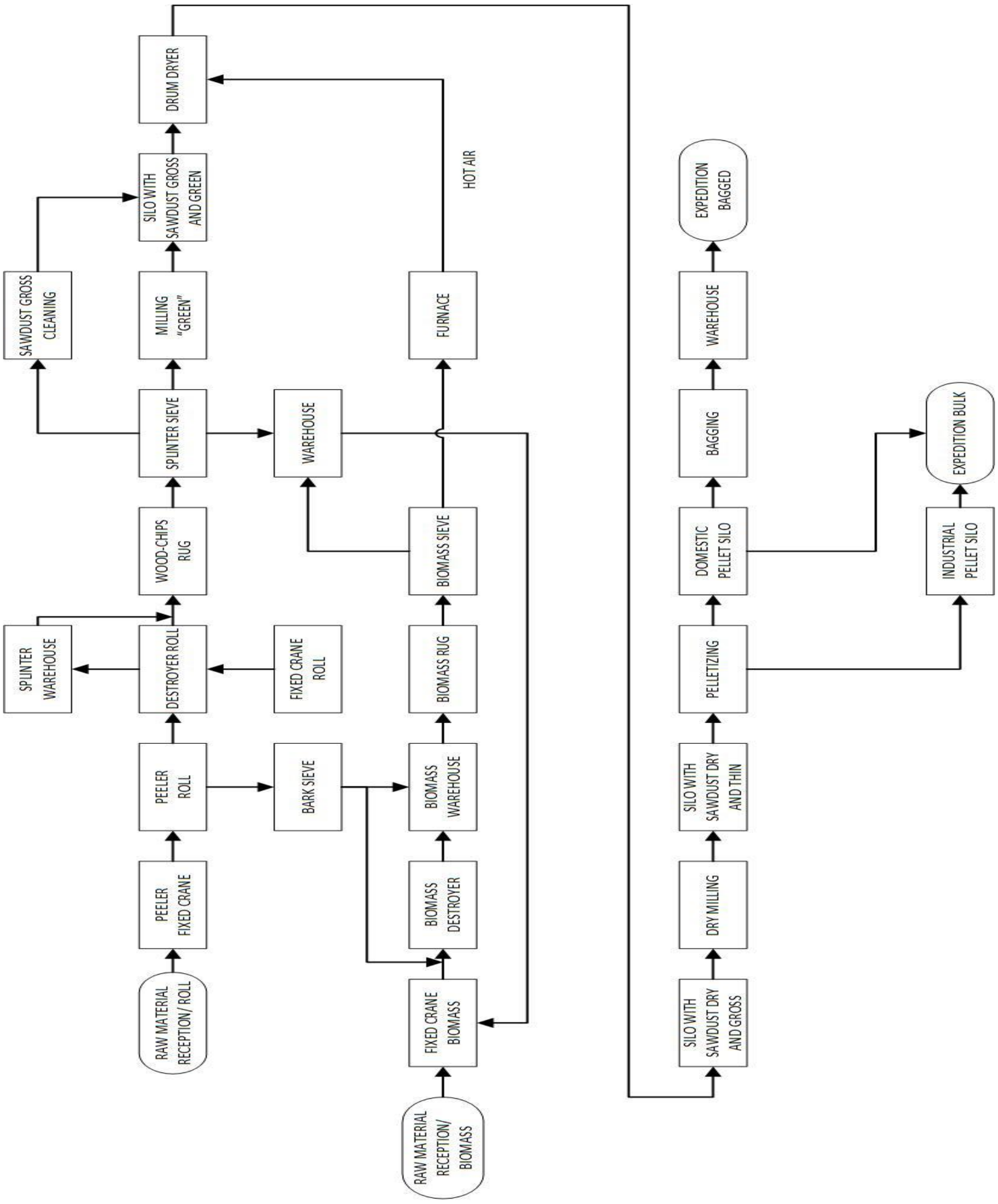
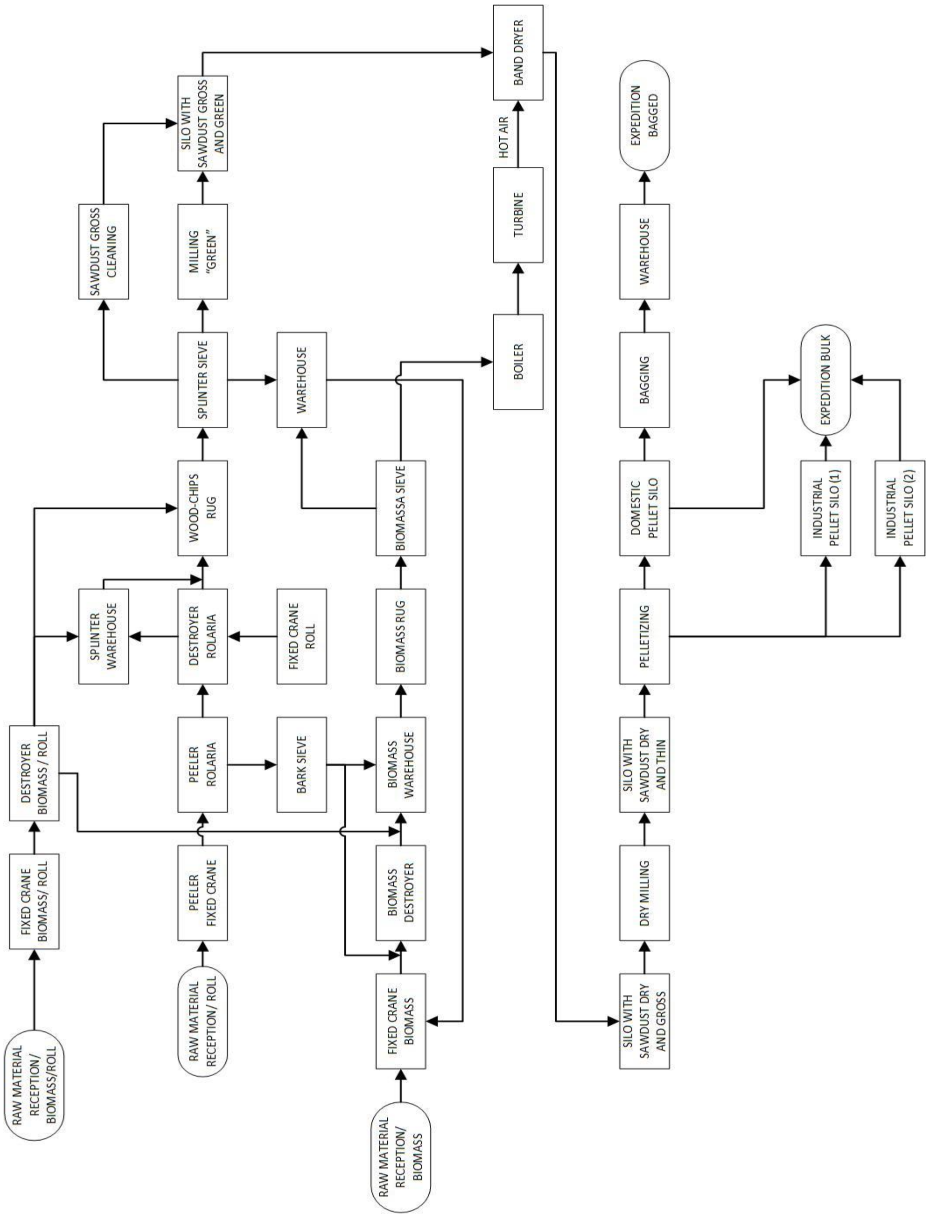
Appendix A

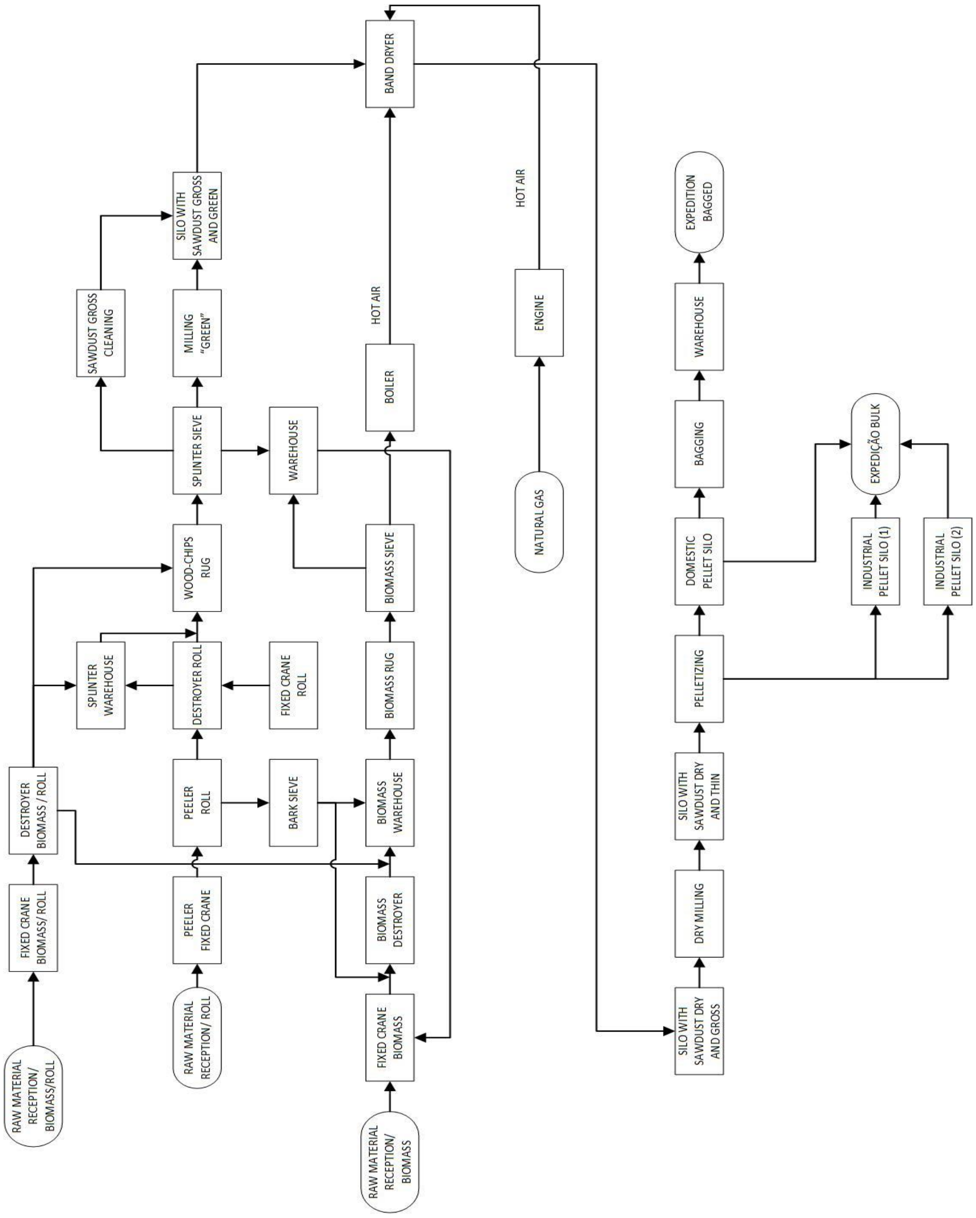
A.1 Flowchart of the current production process



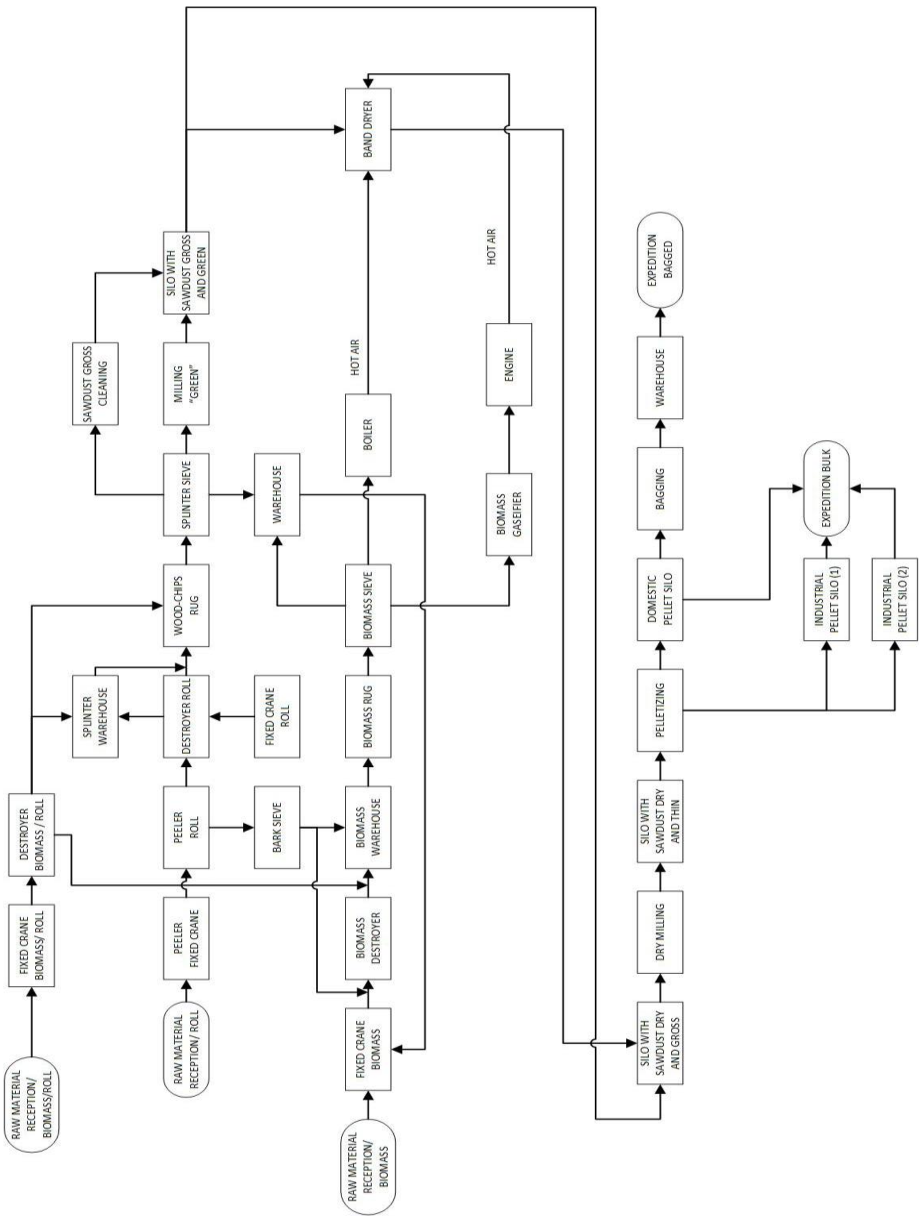
A.2 Flowchart of the current production process after the implementation of the solution described in 4.3



A.3 Flowchart of the current production process after the implementation of the solution described in 4.4

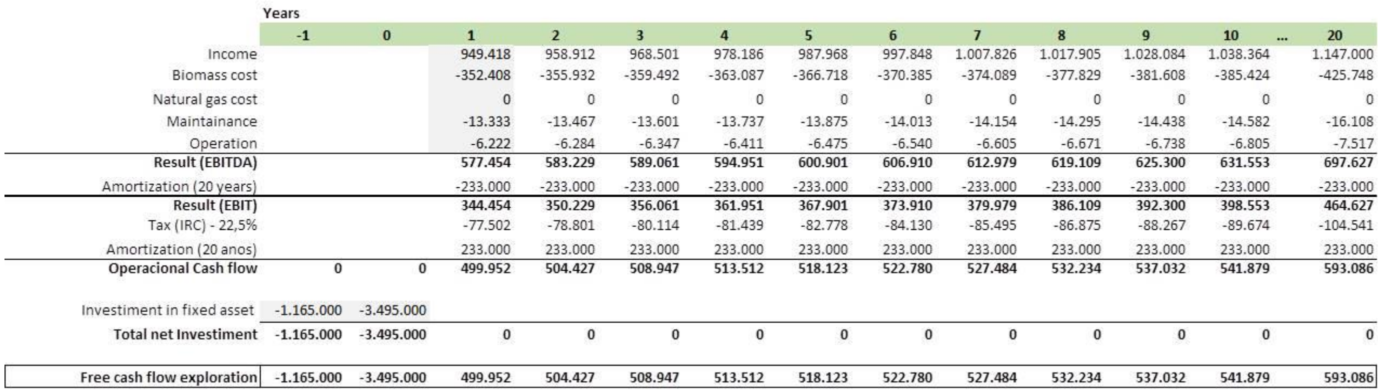


A.4 Flowchart of the current production process after the implementation of the solution described in 4.5



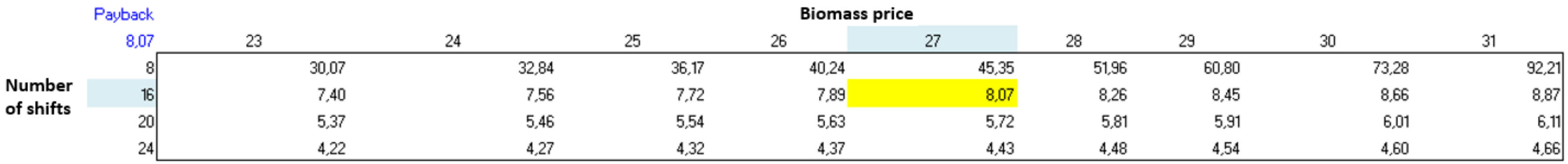
Appendix B

B.1 Project results from the solution described in 4.3

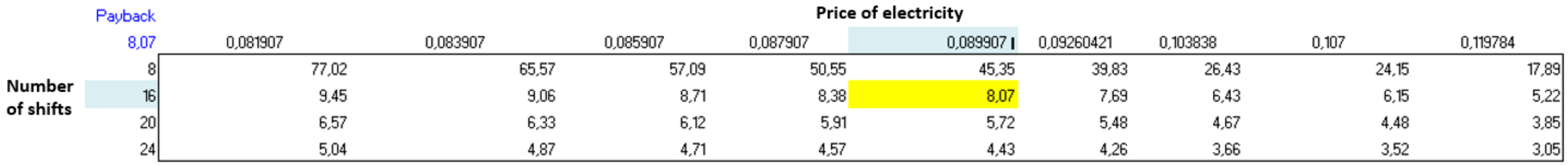


Years	-1	0	1	2	3	4	5	6	7	8	9	10	...	20
Income			949.418	958.912	968.501	978.186	987.968	997.848	1.007.826	1.017.905	1.028.084	1.038.364		1.147.000
Biomass cost			-352.408	-355.932	-359.492	-363.087	-366.718	-370.385	-374.089	-377.829	-381.608	-385.424		-425.748
Natural gas cost			0	0	0	0	0	0	0	0	0	0		0
Maintainance			-13.333	-13.467	-13.601	-13.737	-13.875	-14.013	-14.154	-14.295	-14.438	-14.582		-16.108
Operation			-6.222	-6.284	-6.347	-6.411	-6.475	-6.540	-6.605	-6.671	-6.738	-6.805		-7.517
Result (EBITDA)			**577.454**	**583.229**	**589.061**	**594.951**	**600.901**	**606.910**	**612.979**	**619.109**	**625.300**	**631.553**		**697.627**
Amortization (20 years)			-233.000	-233.000	-233.000	-233.000	-233.000	-233.000	-233.000	-233.000	-233.000	-233.000		-233.000
Result (EBIT)			**344.454**	**350.229**	**356.061**	**361.951**	**367.901**	**373.910**	**379.979**	**386.109**	**392.300**	**398.553**		**464.627**
Tax (IRC) - 22,5%			-77.502	-78.801	-80.114	-81.439	-82.778	-84.130	-85.495	-86.875	-88.267	-89.674		-104.541
Amortization (20 anos)			233.000	233.000	233.000	233.000	233.000	233.000	233.000	233.000	233.000	233.000		233.000
Operacional Cash flow	0	0	**499.952**	**504.427**	**508.947**	**513.512**	**518.123**	**522.780**	**527.484**	**532.234**	**537.032**	**541.879**		**593.086**
Investiment in fixed asset	-1.165.000	-3.495.000												
Total net Investiment	**-1.165.000**	**-3.495.000**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**		**0**
Free cash flow exploration	**-1.165.000**	**-3.495.000**	**499.952**	**504.427**	**508.947**	**513.512**	**518.123**	**522.780**	**527.484**	**532.234**	**537.032**	**541.879**		**593.086**

IRR	**9,2%**
NPV	**-214.495**
Payback	**8 years e 1 month**
	8,07



	Payback	Biomass price								
	8,07	23	24	25	26	27	28	29	30	31
Number of shifts	8	30,07	32,84	36,17	40,24	45,35	51,96	60,80	73,28	92,21
	16	7,40	7,56	7,72	7,89	8,07	8,26	8,45	8,66	8,87
	20	5,37	5,46	5,54	5,63	5,72	5,81	5,91	6,01	6,11
	24	4,22	4,27	4,32	4,37	4,43	4,48	4,54	4,60	4,66

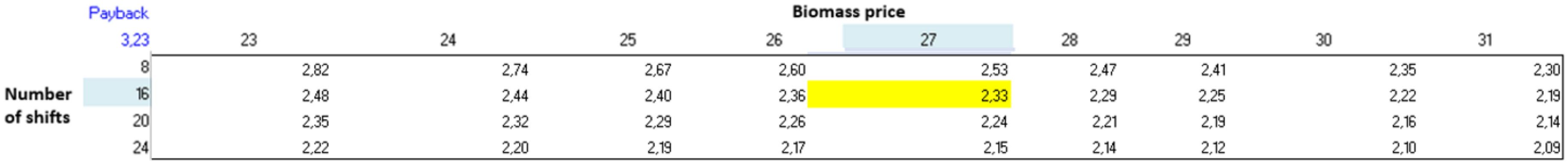


	Payback	Price of electricity								
	8,07	0,081907	0,083907	0,085907	0,087907	0,089907	0,09260421	0,103838	0,107	0,119784
Number of shifts	8	77,02	65,57	57,09	50,55	45,35	39,83	26,43	24,15	17,89
	16	9,45	9,06	8,71	8,38	8,07	7,69	6,43	6,15	5,22
	20	6,57	6,33	6,12	5,91	5,72	5,48	4,67	4,48	3,85
	24	5,04	4,87	4,71	4,57	4,43	4,26	3,66	3,52	3,05

B.2 Project results from the solution described in 4.4

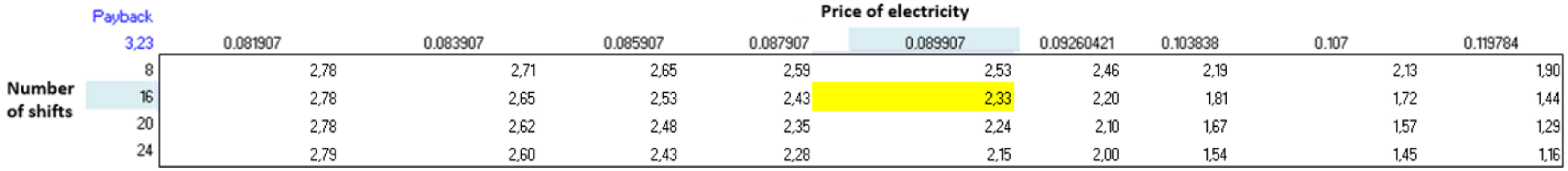
Years	-1	0	1	2	3	4	5	6	7	8	9	10	...	20
Income			1.381.802	1.395.620	1.409.577	1.423.672	1.437.909	1.452.288	1.466.811	1.481.479	1.496.294	1.511.257		1.669.368
Biomass cost			-210.704	-212.811	-214.939	-217.088	-219.259	-221.452	-223.666	-225.903	-228.162	-230.444		-254.553
Natural gas cost			-556.074	-561.634	-567.251	-572.923	-578.653	-584.439	-590.284	-596.186	-602.148	-608.170		-671.798
Maintainance			-79.200	-79.992	-80.792	-81.600	-82.416	-83.240	-84.072	-84.913	-85.762	-86.620		-95.682
Operation			-20.064	-20.265	-20.467	-20.672	-20.879	-21.087	-21.298	-21.511	-21.726	-21.944		-24.239
Result (EBITDA)			**515.761**	**520.919**	**526.128**	**531.389**	**536.703**	**542.070**	**547.491**	**552.966**	**558.495**	**564.080**		**623.095**
Amortization (20 years)			-60.000	-60.000	-60.000	-60.000	-60.000	-60.000	-60.000	-60.000	-60.000	-60.000		-60.000
Result (EBIT)			**455.761**	**460.919**	**466.128**	**471.389**	**476.703**	**482.070**	**487.491**	**492.966**	**498.495**	**504.080**		**563.095**
Tax (IRC) - 22,5%			-102.546	-103.707	-104.879	-106.063	-107.258	-108.466	-109.685	-110.917	-112.161	-113.418		-126.696
Amortization (20 anos)			60.000	60.000	60.000	60.000	60.000	60.000	60.000	60.000	60.000	60.000		60.000
Operacional Cash flow	**0**	**0**	**413.215**	**417.212**	**421.249**	**425.327**	**429.445**	**433.604**	**437.805**	**442.048**	**446.334**	**450.662**		**496.399**
Investiment in fixed asset	-300.000	-900.000												
Total net Investiment	-300.000	-900.000	0	0	0	0	0	0	0	0	0	0		0
Free cash flow exploration	**-300.000**	**-900.000**	**413.215**	**417.212**	**421.249**	**425.327**	**429.445**	**433.604**	**437.805**	**442.048**	**446.334**	**450.662**		**496.399**

IRR	**32,7%**
NPV	**2.083.205**
Payback	**2 years e 3 months**
	2,33



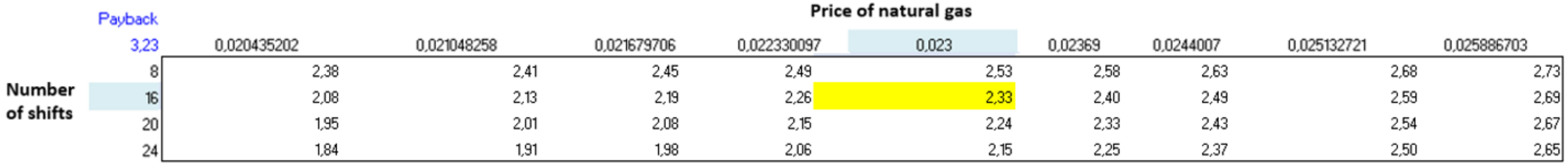
Biomass price

	Payback 3,23	23	24	25	26	27	28	29	30	31
Number of shifts	8	2,82	2,74	2,67	2,60	2,53	2,47	2,41	2,35	2,30
	16	2,48	2,44	2,40	2,36	2,33	2,29	2,25	2,22	2,19
	20	2,35	2,32	2,29	2,26	2,24	2,21	2,19	2,16	2,14
	24	2,22	2,20	2,19	2,17	2,15	2,14	2,12	2,10	2,09



Price of electricity

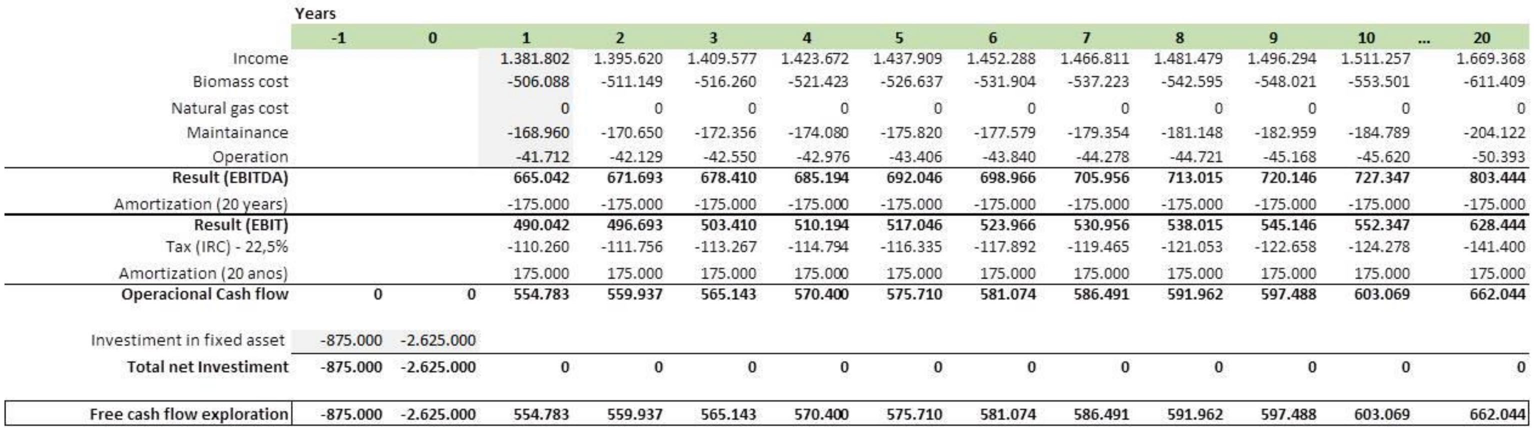
	Payback 3,23	0.081907	0.083907	0.085907	0.087907	0.089907	0.09260421	0.103838	0.107	0.119784
Number of shifts	8	2,78	2,71	2,65	2,59	2,53	2,46	2,19	2,13	1,90
	16	2,78	2,65	2,53	2,43	2,33	2,20	1,81	1,72	1,44
	20	2,78	2,62	2,48	2,35	2,24	2,10	1,67	1,57	1,29
	24	2,79	2,60	2,43	2,28	2,15	2,00	1,54	1,45	1,16



Price of natural gas

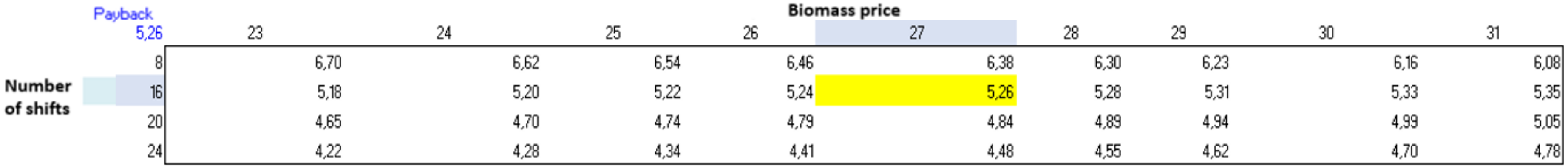
	Payback 3,23	0,020435202	0,021048258	0,021679706	0,022330097	0,023	0,02369	0,0244007	0,025132721	0,025886703
Number of shifts	8	2,38	2,41	2,45	2,49	2,53	2,58	2,63	2,68	2,73
	16	2,08	2,13	2,19	2,26	2,33	2,40	2,49	2,59	2,69
	20	1,95	2,01	2,08	2,15	2,24	2,33	2,43	2,54	2,67
	24	1,84	1,91	1,98	2,06	2,15	2,25	2,37	2,50	2,65

B.3 Project results from the solution described in 4.5

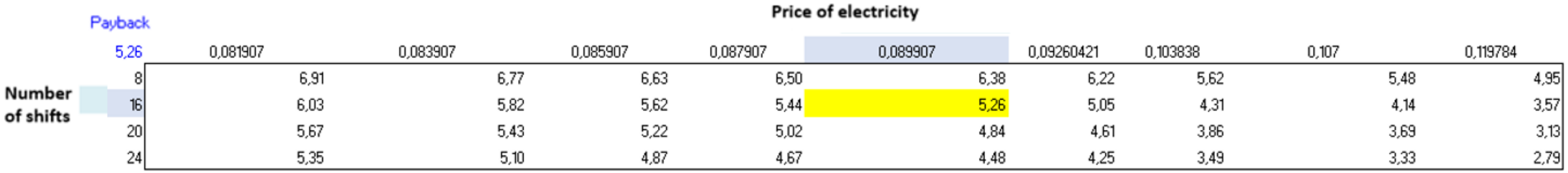


Years	-1	0	1	2	3	4	5	6	7	8	9	10	...	20
Income			1.381.802	1.395.620	1.409.577	1.423.672	1.437.909	1.452.288	1.466.811	1.481.479	1.496.294	1.511.257		1.669.368
Biomass cost			-506.088	-511.149	-516.260	-521.423	-526.637	-531.904	-537.223	-542.595	-548.021	-553.501		-611.409
Natural gas cost			0	0	0	0	0	0	0	0	0	0		0
Maintainance			-168.960	-170.650	-172.356	-174.080	-175.820	-177.579	-179.354	-181.148	-182.959	-184.789		-204.122
Operation			-41.712	-42.129	-42.550	-42.976	-43.406	-43.840	-44.278	-44.721	-45.168	-45.620		-50.393
Result (EBITDA)			**665.042**	**671.693**	**678.410**	**685.194**	**692.046**	**698.966**	**705.956**	**713.015**	**720.146**	**727.347**		**803.444**
Amortization (20 years)			-175.000	-175.000	-175.000	-175.000	-175.000	-175.000	-175.000	-175.000	-175.000	-175.000		-175.000
Result (EBIT)			**490.042**	**496.693**	**503.410**	**510.194**	**517.046**	**523.966**	**530.956**	**538.015**	**545.146**	**552.347**		**628.444**
Tax (IRC) - 22,5%			-110.260	-111.756	-113.267	-114.794	-116.335	-117.892	-119.465	-121.053	-122.658	-124.278		-141.400
Amortization (20 anos)			175.000	175.000	175.000	175.000	175.000	175.000	175.000	175.000	175.000	175.000		175.000
Operacional Cash flow	**0**	**0**	**554.783**	**559.937**	**565.143**	**570.400**	**575.710**	**581.074**	**586.491**	**591.962**	**597.488**	**603.069**		**662.044**
Investiment in fixed asset	-875.000	-2.625.000												
Total net Investiment	-875.000	-2.625.000	0	0	0	0	0	0	0	0	0	0		0
Free cash flow exploration	-875.000	-2.625.000	554.783	559.937	565.143	570.400	575.710	581.074	586.491	591.962	597.488	603.069		662.044

IRR	15,1%
NPV	1.186.607
Payback	5 years e 3 months
	5,26



Payback 5,26		23	24	25	26	27	28	29	30	31
		Biomass price								
Number of shifts	8	6,70	6,62	6,54	6,46	6,38	6,30	6,23	6,16	6,08
	16	5,18	5,20	5,22	5,24	5,26	5,28	5,31	5,33	5,35
	20	4,65	4,70	4,74	4,79	4,84	4,89	4,94	4,99	5,05
	24	4,22	4,28	4,34	4,41	4,48	4,55	4,62	4,70	4,78



Payback 5,26		0,081907	0,083907	0,085907	0,087907	0,089907	0,09260421	0,103838	0,107	0,119784
		Price of electricity								
Number of shifts	8	6,91	6,77	6,63	6,50	6,38	6,22	5,62	5,48	4,95
	16	6,03	5,82	5,62	5,44	5,26	5,05	4,31	4,14	3,57
	20	5,67	5,43	5,22	5,02	4,84	4,61	3,86	3,69	3,13
	24	5,35	5,10	4,87	4,67	4,48	4,25	3,49	3,33	2,79