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

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Abstract

Cogeneration is the generation of multiple forms of useful energy at the same time, in most cases, electrical and thermal energy, in an integrated system, using a single fuel source. Although cogeneration processes were already used several years ago, it was from 2008 that cogeneration had the highest growth and utilization in the industrial system in Portugal. This growth was mainly due to measures taken to ensure that industrialists choose to use more environmentally-friendly systems that allow them to rationalize resources. These measures are still in force today. Another major factor that benefits cogeneration projects is the financial profitability to which they are associated. 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 electricity and raw material.

Although cogeneration is already well developed and there are technologies that allow users to achieve good results in its operation, new technologies are being developed, the so-called emerging technologies, which promise to improve cogeneration exploitation results and increase profitability.

The purpose of this paper is to study which cogeneration project, taking into account the available technologies and primary energy sources, which best applies to the case study from a technical, environmental and economic point of view.

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

1. Introduction

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.

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.

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.[1] 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 its 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. [2]

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. [3]

2. Case study

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 companys 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.

2.1. 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. The electricity consumed corresponds to about 2 MWh per month.

2.2. 3.3. 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. Monthly biomass consumption in the plant is around 1,500 tons per month

3. Proposed solution

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.

The starting point for the project was the production of 2.000 kWh 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, avoiding the burning of the chips, thus becoming less dark and having more quality.

3.1. Solution using steam turbine

The boiler has to produce hot gases in sufficient quantity and temperature to ensure a temperature of 100C 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.

Figure 1 explains the inclusion of this cogeneration system in the manufacturing process, in a summarized way.

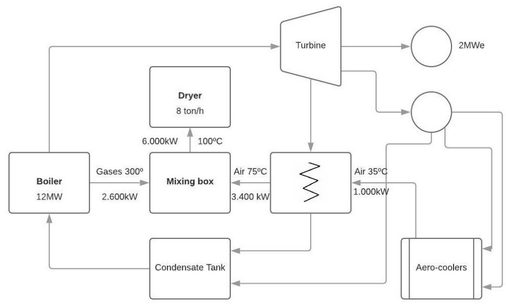

Figure 1: Cogeneration solution flowchart using a steam turbine

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.

3.2. Solution using a natural gas-fired internal combustion engine

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, 100C 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.

In the figure below we can observe the inclusion of this cogeneration system in the factory production process.

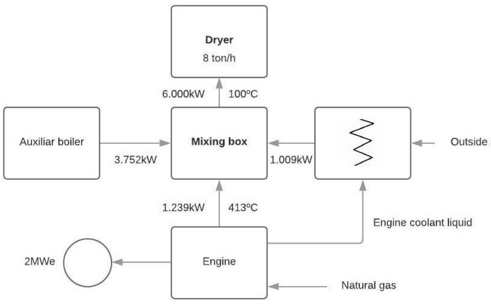

Figure 2: Cogeneration solution flowchart using a biogas-fired internal combustion engine.

3.3. Solution using a biogas-fired internal combustion engine

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 100C 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.

In the figure below we can observe the inclusion of this cogeneration system in the factory production process.

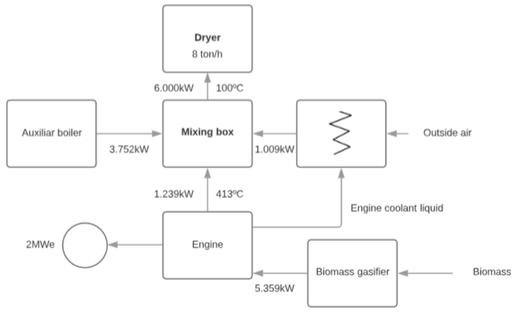

Figure 3: Cogeneration solution flowchart using an internal combustion engine with biogas.

4. Exploration results

For each of the solutions, a technical and economic study was carried out to analyze the profitability of the project. The profitability indicators were payback, IRR and NPV.

From an economic point of view, for a base scenario, we consider an average price of 27 /ton for the cost of biomass, 0,023 /kWh for natural gas and 0,089907 /kW for electricity by averaging peak, off-peak, valley and super-valley electricity prices in January 2018.

4.1. Solution using steam turbine

Table 1 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 power (biomass) to produce 2 MWe	6600 kW
Consumption of biomass	2472 kg/h

Table 1: Energy balance of the solution using a steam turbine.

Table 2 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.

For this solution, maintenance costs of 2.53 €/ hour and operating costs of 1.18 €/ hour were considered. The investment cost is 4.660.000,00 €.

Table 3 shows the payback calculation, varying the number of shifts to operate at the factory.

Consumption of electricity considering that the factory works 11 months a year, 30 days a month and 24 hours a day	
Weighted average price	0,089.907 €/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 consumption	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 2: Annual savings and annual biomass cost

	3 Shifts 24h	2 Shifts 16h	1 Shift 8h
Income (€)	1,424, 126.00	949,417.92	474,708.67
Biomass costs (€)	-528, 612.0	-352, 408.32	-176, 204.0
Natural Gas Cost (€)			
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 3: Project results according to the number of working hours.

The following sensitivity analysis was therefore performed by combining the number of plant shifts with the biomass price change and the cost of acquiring energy from the grid:

	Biomass price (€/ton)			
	Pay-back 8.07	23	27	31
Number of working hours (h)	8	30.07	45.35	92.21
	16	7.40	8.07	8.87
	20	5.37	5.72	6.11
	24	4.22	4.43	4.66

Table 4: Sensitivity analysis combining the number of shifts with biomass price.

	Price of electricity (€/ton)			
	Pay-back 8.07	0.081907	0.089907	0.119784
Number of working hours (h)	8	77.02	45.35	17.89
	16	9.45	8.07	5.22
	20	6.57	5.72	3.85
	24	5.04	4.43	3.05

Table 5: Sensitivity analysis combining the number of shifts with the electricity price.

4.2. Solution using a natural gas-fired internal combustion engine

Table 6 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
Heat from engine gases	1239 kW
Heat from engine cooling circuit	1009 kW
Total thermal power from engine	2248 kW
Additional power (biomass)	3752 kW

Table 6: Energy balance of the solution using natural gas-fired internal combustion engine.

Table 7 shows the calculations of energy savings due to the cogeneration system as well as biomass and natural gas consumption and their costs.

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 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:	
Natural gas consumption of the engine	4579 kWh
Cost of natural gas	0.023 €/kWh
Total cost of natural gas per year	834,110.64 €/year
Additional biomass cost considering that the factory works 11 months a year, 30 days a month and 24 hours a day	
Biomass consumption	1478 kg/h
Biomass price	27 €/ton
Annual biomass cost	316,055.52 €/year
Total cost of natural gas and biomass	
Total cost	1,149,254 €/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 costs	432,384 €/year
Total cost of natural gas and final biomass	716,870 €/year

Table 7: Electricity consumed and its cost, energy savings and the biomass consumption and its cost

For this solution, maintenance costs of 15 €/ hour and operating costs of 3.80 €/ hour were considered. The investment cost is 1.200.000,00 €.

For an analysis of project profitability a payback calculation was made by varying the number of shifts to operate at the factory:

	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 Cost (€)	- 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 8: Project results according to the number of working hours.

The following sensitivity analysis was therefore performed by combining the number of plant shifts with the biomass price change and the cost of acquiring energy from the grid:

	Biomass price (€/ton)			
	Payback 2.33	23	27	31
Number of working hours (h)	8	2.82	2.53	2.30
	16	2.48	2.33	2.19
	20	2.35	2.24	2.14
	24	2.22	2.15	2.09

Table 9: Sensitivity analysis combining the number of shifts with the biomass price.

	Price of electricity (€/ton)			
	Payback 2.33	0.081907	0.089907	0.119784
Number of working hours (h)	8	2.78	2.53	1.90
	16	2.78	2.33	1.44
	20	2.78	2.24	1.29
	24	2.79	2.15	1.16

Table 10: Sensitivity analysis combining the number of shifts with the electricity purchase price.

	Price natural gas (€/KWh)			
	Pay-back 2.33	0.0204	0.023	0.0259
Number of working hours (h)	8	2.38	2.53	2.73
	16	2.08	2.33	2.69
	20	1.95	2.24	2.67
	24	1.84	2.15	2.65

Table 11: Sensitivity analysis combining the number of shifts with the purchase price of natural gas.

4.3. Solution using a biogas-fired internal combustion engine

Table 12 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
Heat from engine gases	1097 kW
Heat from engine cooling circuit	989 kW
Total thermal power from engine	2086 kW
Additional power (biomass)	3914 kW

Table 12: Cogeneration solution flowchart using a 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 13 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 the cost of biomass for the Gasifier and 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 cost considering that the factory works 11 months a year, 30 days a month and 24 hours a day	
Biomass consumption	1542 kg/h
Biomass price	27 €/ton
Annual biomass cost	329,741.28 €/year
Total cost of natural gas and 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 costs	432,384 €/year
Total cost of biomass	326,748 €/year

Table 13: Electricity consumed and its cost, energy savings and biomass consumption and its cost.

For this solution, maintenance costs of 32 €/ hour and operating costs of 7.90 €/ hour were considered. The investment cost is 3.500.000,00 €.

For an analysis of project profitability a payback calculation was made by varying the number of shifts to operate at the factory:

	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 Cost (€)	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 14: Project results according to the number of working hours.

The following sensitivity analysis was therefore performed by combining the number of plant shifts with the biomass price change and the cost of acquiring energy from the grid:

	Biomass price (€/ton)			
	Payback 5.26	23	27	31
Number of working hours (h)	8	6.70	6.38	6.08
	16	5.18	5.26	5.35
	20	4.65	4.84	5.05
	24	4.22	4.48	4.78

Table 15: Sensitivity analysis combining the number of shifts with the price of biomass.

	Price of electricity (€/ton)			
	Payback 5.26	0.081907	0.089907	0.119784
Number of working hours (h)	8	6.91	6.38	4.95
	16	6.03	5.26	3.57
	20	5.67	4.84	3.13
	24	5.35	4.48	2.79

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

5. 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.

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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