

# Energetic and Economical Evaluation of the Dimensioning of Cogeneration and Trigeneration Plants

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## Abstract

The management of energy resources is one of the main challenges to be faced worldwide. The increase in energy consumption, the rising price of fossil fuels and a greater environmental concern on a global scale have led to a significant importance of energy efficiency and energy usage.

This paper focuses on the study of cogeneration and trigeneration dimensioning from an economic and energetic point of view. Therefore, a program was developed that allows the testing of different capacities of cogeneration and trigeneration equipments based on the heat and cooling load diagrams of the thermal needs. The aim of this program is to produce a series of economic and energetic results that allow the evaluation of each tested solution.

The case of a building complex was studied and concluded that a trigeneration plant with a 900 kW<sub>e</sub> internal combustion engine allowing steam production associated with a 600 kW<sub>f</sub> double effect lithium bromide absorption chiller would be the best solution enabling a net present value of 635.176€ and an effective primary energy saving of 15,7%.

**KEYWORDS:** Cogeneration, Trigeneration, Effective primary energy saving, Energy efficiency, Load diagrams.

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## 1. Introduction

To evolve towards environmental sustainability it is necessary to mitigate energy consumption by promoting energy efficiency. Portugal is a country with scarce energetic resources, mainly, those who cover the needs of developed countries like oil, coal or natural gas. In 2011, 76,1% of the primary energy consumption was of fossil origin leading to a 77,1% dependence on foreign energy for the same year [1]. With the extinction of the Kyoto Protocol in 2012 and with the worldwide fossil fuels reserves unable to follow the rising energy consumption, the European Union approved in December of 2008 the “EU energy climate package” which considers a series of energetic targets to be fulfilled in 2020 [2]. At a national level it was approved in April of 2010 the “Estratégia Nacional para a Energia” [3] with horizon

also in 2020 and in accordance with the energy climate package which promotes the activity of cogeneration as a means of increasing energy efficiency.

The aim of the present work is the study of the dimensioning of cogeneration and trigeneration plants on the commerce and services sector from an economic and energetic point of view in order to evaluate their feasibility. In order to achieve this goal a tool allowing the testing of different sizes of cogeneration and trigeneration equipments was built and applied to the case of a building complex. Based on the hourly heating and cooling load diagrams the tool was used to delineate the choice and dimension of cogeneration and trigeneration equipments.

## 2. Energy demands of the building complex

The building complex is composed of multiple fractions including, a health clinic, a sports center, a gym, a football stadium and several offices. The total building complex consumption was of 779.727 m<sup>3</sup> of natural gas that fed three boilers and 2.024.442 kWh electricity used in 5 compression chillers.

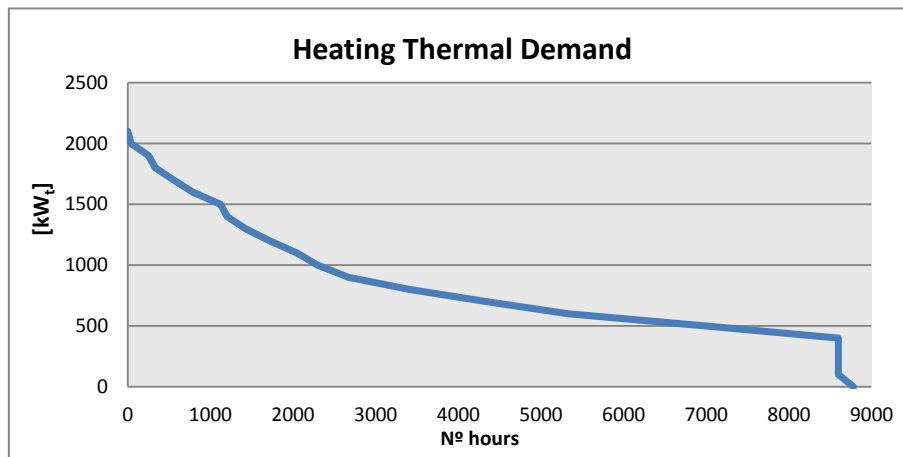


Figure 1 – Heating demand cumulative curve

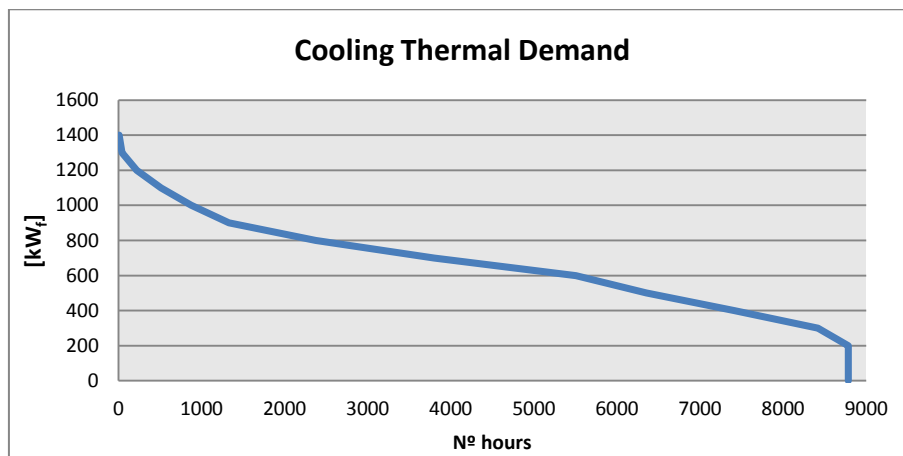
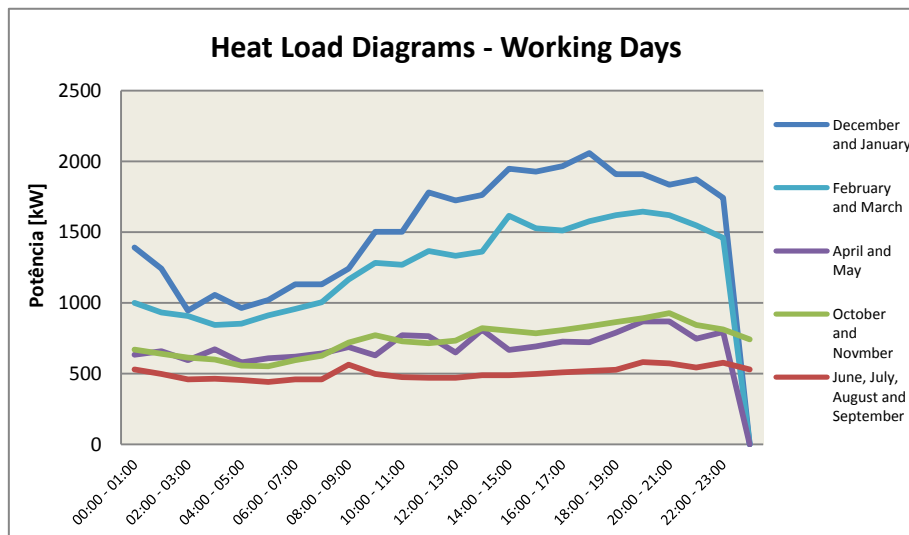
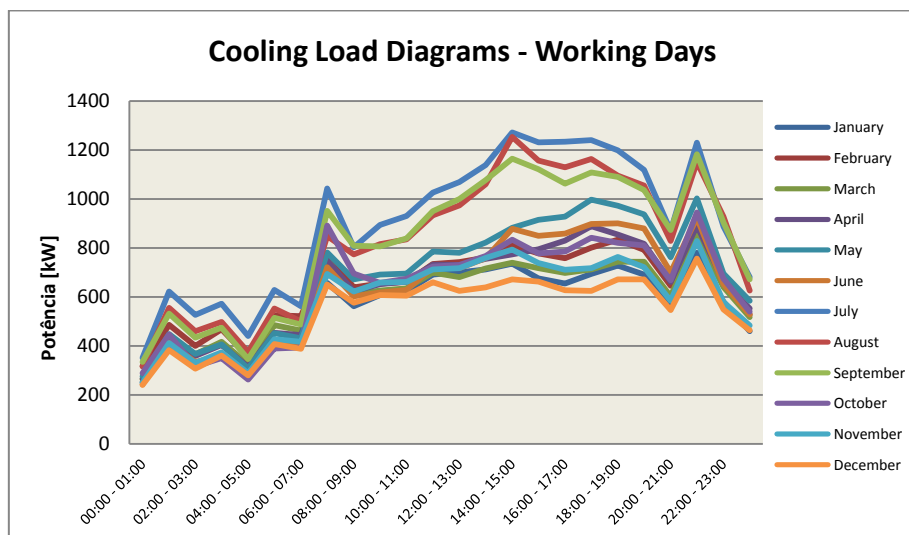


Figure 2 – Cooling demand cumulative curve

Figures 1 and 2 illustrate the heating and cooling demand cumulative curves for the entire building complex. Though this information is useful and enables the user to, for instance, know peak needs it does not provide information of the daily needs. Therefore the hourly load heating and cooling diagrams were built by evaluating the hourly consumption of natural gas and the electricity profile consumption during the day.



**Figure 3 – Heat load diagrams for working days**



**Figure 4 – Cooling load diagrams for working days**

In Figures 3 and 4 it is shown the mean profile of a working day for each month. It was assumed that this profile would remain constant throughout the month. The profile for heating was taken from the gas consumption measurements that were available hour by hour. The cooling load was calculated on the monthly electricity consumption and on the assumption that the energy used for cooling

corresponds to a certain fraction of the total electricity. This fraction was measured on a specific period and was assumed to be similar in all months, excluding only the periods when there are football matches. Similarly load diagrams were also built for Saturdays and Sundays or holidays of each month.

### 3. Plant Configuration

There are several cogeneration technologies available on the market. For the purpose of this work and considering the energy demands of commerce and services buildings, gas turbines and internal combustion engines were chosen as the plants' prime movers once they are considered as mature technologies. As to what concerns trigeneration equipments lithium bromide and ammonia absorption *chillers* were considered, as well as adsorption *chillers*. Due to its high COP/price ratio simple and double effect lithium bromide absorption chillers were the equipments considered for trigeneration in this analysis.

Three working criterias were defined to internal combustion engines: at full load, at partial load and with steam production.

- Full load – The engine will work at full load as long as at least 30% of its thermal energy is consumed, otherwise it shuts down.
- Partial load – The engine will adapt to the thermal needs changing its load until a minimum of 50%. At this point if at least 85% of the thermal energy is at use it will stay on , otherwise it shuts down.
- Steam Production – This engine wil work at full load allowing the production of steam via the exhaust gases.

It is important to consider these different criterias for the internal combustion engines. On the one hand, the degradation of the ratio electricity/heat (electric efficiency increases and thermal decreases) with the load change can be harmful to cogeneration and trigeneration plants. Therefore, the full and partial load behaviors should be considered. On the other hand, steam production on an internal combustion engine is able to trigger a double effect absorption chiller which has a higher COP than a simple effect. For the gas turbines only one behavior was consider that is the full load work with no limitations of thermal energy consumption.

With this description on the cogeneration and trigeneration equipments a total of seven plants can be considered on this analysis:

- Internal Combustion Engine at full load
- Internal Combustion Engine at full load and Simple Effect Absorption Chiller
- Internal Combustion Engine at partial load
- Internal Combustion Engine at partial load and Simple Effect Absorption Chiller
- Internal Combustion Engine steam production and Double Effect Absorption Chiller

- Gas Turbine
- Gas Turbine and Double Effect Absorption Chiller

Each of the above mentioned plants includes a support boiler and a support compression chiller. The boiler is meant to be triggered every time the cogeneration equipment is turned off or when it is not able to fulfill all the heating needs. The compression chiller has the same purpose but for the cooling needs or if there is no absorption chiller present.

In addition, for each available plant configuration two other options were included. The first one concerns the support boiler and the possibility of being turned on to activate or support the absorption chiller. The second one regards the working schedule of the plant. Depending on the period of the day the electric tariff will vary. Therefore the tool was built to enable the testing of each period of the electric tariff as well as the totality of the day.

## 4. Methodology of Analysis

The procedure of analysis consists on, based in the load diagrams of heating and cooling needs, testing the dimension of cogeneration and trigeneration equipments in order to produce economic and energetic results to evaluate the solutions tested.

### 4.1 Economic Analysis

The economic analysis is based on the maximization of the NPV analysis as explained in [4]. The analysis considers the savings in operating costs allowed by the proposed plant when compared to the existing plant. Comparing these savings to the initial investment it is possible to calculate the payback period (PBP), the net present value (NPV) as well as the internal rate of return (IRR) for each solution tested. It was considered a discount rate of 10% for the calculation of this parameters.

### 4.2 Energetic Analysis

The primary energy saving (PES) is the most used index when evaluating the energetic results of cogeneration plants as in [5]. This index defines the savings on primary energy, in percentage terms, that can be achieved by using a cogeneration plant rather than a conventional plant for the same quantities of electricity ( $E_{cog}$ ) and heat ( $H_{cog}$ ) produced in cogeneration:

$$PES = 1 - \frac{1}{\frac{\eta_{t,cog} + \eta_{e,cog}}{\eta_{t,ref} + \eta_{e,ref}}} = \frac{\frac{H_{Cog}}{\eta_{t,ref}} + \frac{E_{Cog}}{\eta_{e,ref}} - F_{Cog}}{\frac{H_{Cog}}{\eta_{t,ref}} + \frac{E_{Cog}}{\eta_{e,ref}}} \quad (1)$$

$F_{cog}$  is the fuel consumed in cogeneration, being  $\eta_{t,cog}$  and  $\eta_{e,cog}$  the thermal and electric efficiencies of cogeneration.  $\eta_{t,ref}$  and  $\eta_{e,ref}$  are the reference thermal and electric efficiencies which for Portugal are 90% and 55%. The PES defined is characteristic of the cogeneration installation and does not reflect the actual primary energy saving in the target application that is the heat consumer. To better estimate the PES it is necessary to compare the energy savings obtained in cogeneration and the total amount of fuel consumed by the power plant. This index is referred in [4] and [6] under the name absolute primary energy saving ( $PES_{Abs}$ ) calculated by:

$$PES_{Abs} = \frac{\frac{H_{Cog}}{\eta_{t,ref}} + \frac{E_{Cog}}{\eta_{e,ref}} - F_{Cog}}{\frac{H_{Total}}{\eta_{t,ref}} + \frac{E_{Total}}{\eta_{e,ref}}} \quad (2)$$

Where  $H_{Total}$  and  $E_{Total}$  are the total needs of heat and electricity to be satisfied by the conventional plant.

When trigeneration plants are considered the heat produced in cogeneration is not only meant for heating but it is also used to activate an absorption *chiller*. Therefore the cogeneration heat can be divided in:

$$H_{Cog} = H_h + H_{Abs} \quad (3)$$

$H_h$  refers to the heat used to cover the heating needs and  $H_{Abs}$  refers to the heat used in the absorption *chiller*. The primary energy required to produce  $H_h$  is calculated as:

$$Primary\ Energy\ H_h = \frac{H_h}{\eta_{t,ref}} \quad (4)$$

When calculating the primary energy for  $H_{Abs}$ , PES and  $PES_{Abs}$  indexes the same calculation as in Equation 4. However, this assumption is wrong because in a trigeneration plant the primary energy related to  $H_{Abs}$  should be the primary energy of the electricity required to generate the cooling energy, in a compression *chiller*, that the  $H_{Abs}$  generates in an absorption *chiller*. Therefore, its primary energy calculation should be:

$$Primary\ Energy\ H_{Abs} = \frac{H_{Abs} \cdot COP_{CA}}{\eta_{e,ref} \cdot COP_{CC}} \quad (5)$$

Where  $COP_{CA}$  and  $COP_{CC}$  are the efficiencies of the absorption and compression *chillers*. When comparing the two ways of calculating the primary energy for  $H_{Abs}$  the following condition can be achieved:

$$\frac{1}{\eta_{t,ref}} > \frac{COP_{CA}}{\eta_{e,ref} \cdot COP_{CC}} \quad (6)$$

This condition is true for the typical values of the compression and absorption chillers efficiencies meaning that the PES and PES<sub>Abs</sub> are considering, for trigeneration plants, primary energy that is not being saved.

A new index called the effective primary energy saving (PEP<sub>Eff</sub>) is defined that can truly measure the savings between a trigeneration plant and a conventional plant. It can be calculated as:

$$PES_{Ef} = \frac{\frac{H_h}{\eta_{t,ref}} + \frac{H_{Abs} \cdot COP_{CA}}{\eta_{e,ref} \cdot COP_{CC}} + \frac{E_{Cog}}{\eta_{e,ref}} - F_{Cog}}{\frac{H_{Total}}{\eta_{t,ref}} + \frac{E_{Total}}{\eta_{e,ref}}} \quad (7)$$

In the energetic analysis along with PES<sub>Eff</sub>, results concerning the reduction of gases with greenhouse effects and the percentage of totals needs satisfied are also produced.

### 4.3 Equipment Parameters

In [4-8] the authors consider the sizing of cogeneration and trigeneration plants but keep the equipment parameters constant throughout their analysis.

In the present work data was gathered that allowed the developed tool to compute the change of the nominal electric and thermal efficiencies of internal combustion engines and gas turbines with the electric power supplied.

For the case of internal combustion engines with load change, the decrease of the electric efficiency and the increase of the thermal efficiency with the load reduction as also considered. These changes on the electric and thermal efficiencies are fundamental because they change the electricity/heat ratio of the cogeneration equipment.

## 5. Case Study

This section presents the results of the analysis for the test case described before. Figures 5 and 6 show the NPV and PES<sub>Eff</sub> when testing an internal combustion engine allowing steam production in cogeneration or in trigeneration with a double effect absorption *chiller* having a total working schedule and without triggering the auxiliary boiler to support the absorption *chiller*. In the figures the bottom axis represents the electric power of the cogeneration equipment and the right column represents the different cooling powers of the *chiller* tested ranging from 0 in cogeneration to a total of 1800 kW.

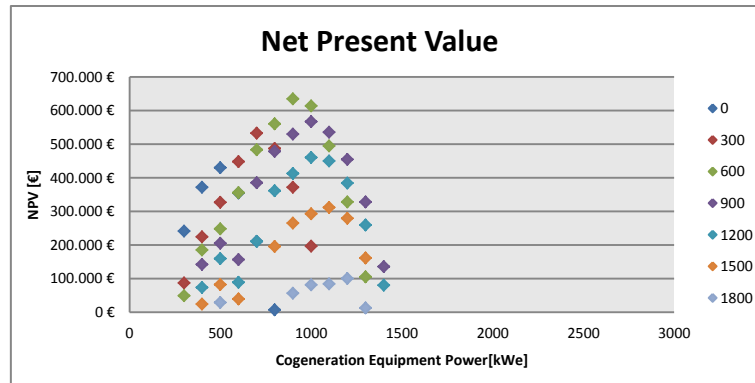


Figure 5 – Net present value for the internal combustion engine with steam production case

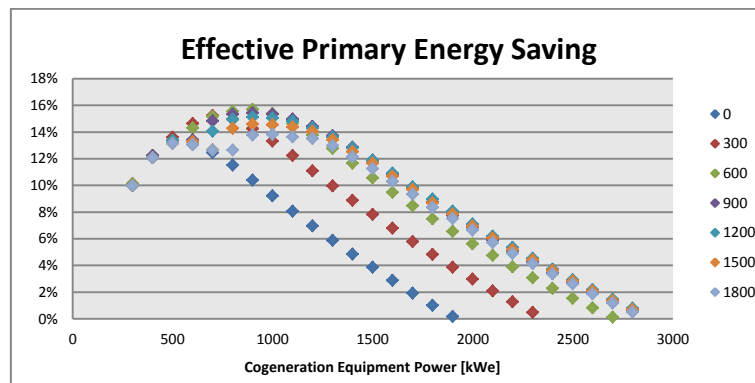


Figure 6 – Effective primary energy saving for the internal combustion engine with steam production case

A similar analysis was carried out for the cases of the internal combustion engine at full load, with load change and for the gas turbines. The goal of the analysis is to choose the most feasible size for the plant. Therefore for each case tested the solution that maximizes the NPV is presented in Table 1.

All the results in Table 1 were obtained for a total working schedule (including all the tariff periods) without triggering the auxiliary boiler to support the absorption chiller. The gas turbine scenario is not presented in Table 1 because it failed to present favorable economic or energetic solutions.

Table 1 – Results achieved for the best solution of each scenario calculated

Scenario	I. Engine – Full Load	II. Engine – Load Change	III. Engine – Steam Production
Best Scenario Solution	Engine – 800 kW Chiller – 300 kW	Engine – 700 kW	Engine – 900 kW Chiller – 600 kW
Operating Costs Savings [€/year]	188.004	173.855	230.354
Initial investment [€]	1.196.305	930.950	1.325.958
PBP [years]	5,9	5,4	5,8
NPV [€]	489.972	549.174	635.176
IRR [%]	19,8	22,6	20,5
PES [%]	21	21	21
PEP <sub>ef</sub> [%]	14,1	15,4	15,7
GHG reduction [ton CO <sub>2,eq</sub> ]	1164	993	1383
Total thermal needs satisfied [%]	46	35	65



From the Table 1 analysis and from an economic point of view the solution of scenario III is the one accomplishing a great NPV despite having the greatest initial investment. In economic terms this solution only loses in terms of PBP and IRR to the one presented in scenario II because the latter is a cogeneration plant with the lowest initial investment.

In energetic terms the scenario III solution was the one accomplishing the biggest  $PES_{Ef}$ , the biggest GHG reduction as well as the most thermal needs satisfied while being able to maintain the economic feasibility.

The PES did not reveal itself as a good method for comparing plants with different sizes remaining constant for all the three solutions presented. On the other hand, the  $PES_{Ef}$  changed among the solutions considered enabling to find the best energetic solution.

When comparing the solutions presented in scenario I and II the economic analysis is favorable the solution presenting load change meaning that the capability to adapt to the thermal needs stands out when compared to the decrease in the electricity/heat ratio with the load decrease.

Only for the case of an engine with load change is a cogeneration plant the best solution. For the remaining cases despite the increase in the initial investment, the increase in the operating costs savings allows for the economic feasibility.

All solutions considered the one that presents itself as the best solution for the case study was a trigeneration plant with a 900 kW<sub>e</sub> internal combustion engine allowing steam production associated with a 600 kW<sub>f</sub> double effect lithium bromide absorption chiller would be the best solution enabling a net present value of 635.176€ and an effective primary energy saving of 15,7%.

## 6. Conclusions

The present paper pointed out the importance of determining the best size, running conditions and equipment technologies when making investment decisions such as cogeneration and trigeneration plants. A tool for the sizing of cogeneration and trigeneration plants was built and the effective primary energy savings was presented as an index to evaluate different sizes of trigeneration plants.

The carried out tests revealed that in a energetic context such as a building complex a trigeneration plant composed of an internal combustion engine allowing steam production and a double effect absorption chiller is the best choice of technologies to be adopted. If correctly dimensioned the plant proposed can achieve considerable energy savings and reduce the operating costs. Gas turbines did not reveal viable for plants in the commerce and services sector due to their low electricity/heat ratio. Internal combustion engines with load change achieve better economic results than the ones at

full load. The  $PES_{Ef}$  proved to be a better method than the PES when comparing different sizes of trigeneration plants.

When making investments as such the need for reduced capital costs and reduced payback periods very often orientates choices for a less expensive kind of plant in detriment of environmental and energetic aspects that should be priorities.

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