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Study of different cogeneration alternatives for a Spanish hospital center

C.J. Renedo *, A. Ortiz, M. Mañana, D. Silió, S. Pérez

Department of Electrical and Energy Engineering, ETSIIT, University of Cantabria, Av Los Castros s/n, 39005 Santander, Spain

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Abstract

In the present article, the authors analyze different possibilities for providing heating, air conditioning and hot tap water to a hospital center. For this, several cogeneration systems with diesel engines and gas turbines were considered. From the study of the results, it is observed that the size of the facility and the control strategy have a strong influence on the system economy, showing that the most important parameter is the electricity produced. So, the solutions with diesel engines are more efficient than the equivalent ones with gas turbines, since they have a higher electrical performance.

Keywords: Cogeneration; Electricity; Thermal energy

1. Introduction

Hospitals are generally great consumers of energy, both electrical and thermal. The latter can take several different forms: hot water, heating or cold water for air conditioning. A lower consumption of this energy will contribute not only to a reduction in the running costs of the hospital, but also in the reduction of pollutant emissions that contribute to the greenhouse effect and a lesser dependence of the hospital on the external power supply.

For an optimal efficiency of the facilities, a study of the various alternatives is required before the design is undertaken.

Two different cogeneration types for a hospital center are analyzed, one with diesel engines and another with gas turbines. For each facility, two different control strategies are studied: to maximize the electrical production and to maximize the time of use at full load. The analysis of the results allows a solution to be reached that optimizes values, such as the energy consumption, the yield or the reduction in the emission of CO_2.

2. The hospital

The hospital is made up of 25 buildings totalling around 80,000 m^2, with more than 1000 beds. It is located in the city of Santander and is one of the most prestigious hospital centers on the north coast of Spain. A summary of the climatology data for this area can be found in [1].

3. Power demand in the hospital

The power demand of the hospital can be divided into thermal demand, which consists of heating, hot tap water and air conditioning systems; and electrical demand. It should be noted that the cold water demand for air conditioning is also an electrical demand, since the method used to produce cold water depends on chillers driven by electrical compressors.

The annual thermal demand of the hospital has been divided into three periods based on the heating requirements:

- winter: high heating and hot tap water demand, very slight need for air conditioning (operating rooms);
- spring–autumn: demand for hot tap water and very slight demand for air conditioning;
- summer: demand for hot tap water and high demand for air conditioning.

* Corresponding author. Tel.: +34 942 201382; fax: +34 942 201385.
E-mail address: renedoc@unican.es (C.J. Renedo).

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In each of these three periods, four intervals have been considered in order to describe the variations in the demand for hot tap water during the day. The other thermal demands are also variable, since the occupation of the buildings depends fundamentally on the schedules of the doctors. Thus, the periods of time were:

- 8–15 h: high hot tap water demand;
- 15–20 h: moderate hot tap water demand;
- 20–24 h: slight hot tap water demand;
- 24–8 h: almost null hot tap water demand, only the losses caused by the water circulation in the network.

The demand for hot tap water in the hospital does not depend on the period of the year, but on the time of day. The non-exact coincidence of the daily time intervals in the three periods of the year is a consequence of the annual variation of the temperature of the supplied cold water to the hospital network [2].

The thermal demand data of the hospital for different annual periods and daily intervals can be observed in the Table 1.

The cooling requirements lead to an electrical demand of approximately 3035 MWh_e; two-thirds of this demand takes place in rush hours, the remaining third coming in non-rush hours.

The annual electrical demand of the hospital, including that required for cooling, is more than 13,535 MWh_e/year, of which approximately 75% is produced in rush hours. The whole energy supply is provided by the local electrical company. Fig. 1 shows the monthly electrical demand.

4. Reference case

The reference case studied is that of the initial (current) facilities in the hospital, configured to supply the heat demand with conventional boilers, while the refrigeration system is based on water chillers driven by electrical compressors. The electrical energy for the chillers and the rest of the consumption is taken from the urban network.

Table 1
Thermal necessities of the hospital (kW_{th})

Thermal demand		Heat			Cool
Period	Interval (h)	Hot tap water	Heating	Total (kW_{th})	Total (kW_{th})
Winter	8–14	3093	4200	7293	878
	14–20	2209	3800	5679	548
	20–24	1326	3800	4844	
	0–8	442	4200	4387	
Spring–Autumn	8–14	3012		2846	1097
	14–20	2151		2033	878
	20–24	1291		1220	548
	0–8	430		407	
Summer	8–14	2849		2692	3731
	14–20	2035		1923	3511
	20–24	1221		1154	3292
	0–8	407		385	548

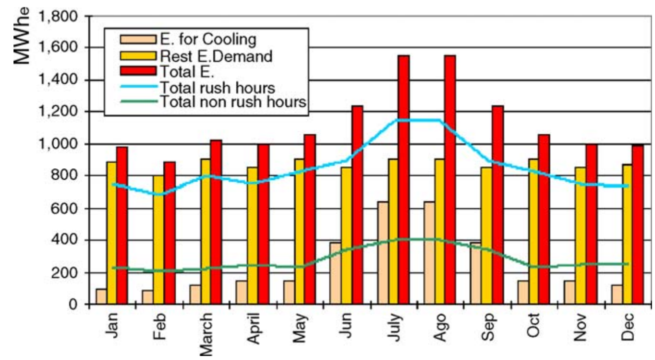

Fig. 1. Monthly electrical demand of hospital (MWh_e).

Taking into account the annual total heating demand, 22,200 MWh_{th}, and considering that the seasonal boiler performance is 85%, the production must be 26,000 MWh_{th}. The fuel used was gas, whose cost per kWh_{th} is €0.022458, so that the annual cost in heating energy is €586,000.

At the same time, the annual cold water demand is 8950 MWh_{th}. The coefficient of performance (COP) of the chillers is 2.95, and approximately two-thirds of the electrical consumption is produced in rush hours. The electricity tariff is €0.0375/kWh_e in rush hours and €0.00826/kWh_e in non-rush hours, resulting in a total cost of approximately €204,000/year for cooling.

The rest of the hospital facilities require 10,500 MWh_e in total; the power demand is approximately 2050 kW_e in workday rush hours, 300 kW_e in the night hours and 775 kW_e in the daytime hours during holidays. Thus, the total cost of the rest of the electricity consumed is €763,600/year. And adding all the costs, it results approximately €1,553,000/year.

5. New cogeneration alternatives

In this section, different cogeneration alternatives with diesel engines and gas turbines are analyzed. Possible solutions using steam were discarded beforehand, due to their complexity and the difficulties in handling it for the hospital maintenance personnel, so combined cycled solutions have not been considered.

Cogeneration systems do not pose a problem in the case of producing more electrical energy than that required for one's own consumption, since Spanish law establishes that this extra energy must be absorbed by the electrical company. Moreover, these systems can represent not only a saving in power and costs for the hospital, but also constitute a safeguard against possible failures in the electrical supply, reducing the external dependency.

In order to optimize cogeneration facilities, the ideal situation would be for the thermal demand of the hospital to be uniform throughout the day and the year. However, this does not happen in practice and the demand is subjected to important variations. Thus, if the alternatives are calculated to cover the maximum thermal demands, then during many hours per year the facilities will be working at low load, or there may even be shutdowns. Thus, special care must be taken when it comes to selecting the cogeneration power, since excess power leads to solutions that are not economically attractive.

In order to decide on the power of the cogeneration facility, the thermal demand must be studied. If the amount of heat is great, this implies that the installation does not fulfill the equivalent electrical yield required by the law to be declared a cogenerator. Therefore, the electrical company is not forced to buy the excess of electrical production. However, the solutions adopted must consider not only economic aspects, but also power and environmental aspects, which tend to increase the efficiency of the facilities, avoiding unnecessary power consumption.

For each of the studied solutions, two different alternatives were considered:

- to maximize the electrical production;
- to maximize the time of use at full load.

The first of the alternatives means greater cogeneration size, since to maximize the electrical production the installation must be designed based on the maximum thermal demand, a situation that takes place in winter. It should take into account that the cogeneration should work properly in periods where the thermal demand is lower, such as autumn and spring, and at partial load, since the operation must respond to the thermal demand.

In the second option, the installation is designed based on the minimum thermal demand, which occurs in summer. In this way, the facility can work all the year round at full load, taking advantage of high efficiency of the cogeneration system permanently. During periods of great thermal demand, part of this must be satisfied by auxiliary elements.

Another important aspect is the electricity tariff, since the existence of tariffs that charge more or less depending on the time of day determines the operating program of the facilities. Considering the price difference in the kWh_e between the nocturnal tariff and the diurnal one, one reaches the conclusion that the cogeneration power station must remain shut down during non-rush hours (nocturnal schedule and non-working days). The reason is that the kWh_e bought at the nocturnal tariff is cheaper than that produced by the cogeneration. This means that the cogeneration should be used 16 h/day, 250 days/year (4000 h/year).

5.1. Cogeneration with diesel engine

The alternative consists of the installation of one or several diesel engines whose axes drag the electrical generators. As electrical and thermal yields of this installation, the values 36 and 48% have been considered, respectively [6–8].

Thus, part of the electrical energy required by the hospital is produced there and, at the same time, residual heat is obtained from the refrigeration water of the engines and also from the exhaust gases. The resulting hot water is used to satisfy the heating and hot tap water demands. In the case where the thermal demand is greater than that supplied by cogeneration, conventional boilers will be necessary to provide the rest of the thermal demand.

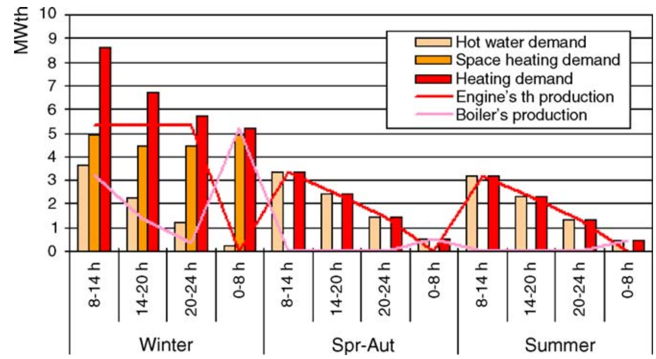

Fig. 2. Thermal balance in MW_{th} during working days with two engines of 2500 and 1500 kW_e.

Meanwhile, the cool water needs for the air conditioning are covered with a chiller driven by an electrical compressor.

5.1.1. Cogeneration with diesel engine and maximum electrical production

In this option, a cogeneration facility of 4000 kW_e has been considered. In order to avoid reducing the installation performance, the engines should work near their rated load. For this reason, it was decided to divide the total power between two engines of 2500 and 1500 kW_e, allowing the engines to work not far from the rated load during all the periods they are in use.

Figs. 2 and 3 show the thermal balance for demand-production during the working days and the monthly electrical balance for this option.

The cogeneration is able to provide almost all the heat required by the hospital in the working days of summer, spring and autumn, covering a very significant part of the winter thermal demand (see Fig. 2).

The auxiliary boilers have to provide the thermal energy that the cogeneration is not able to supply, but they must also have sufficient power to cover the hospital's thermal demand when the cogeneration is stopped, due to a failure or during a holiday. Therefore, the total power has to be at least equal to the maximum thermal demand, 7300 kW_{th}. This total power of the boilers is independent of the alternative considered.

Fig. 3 shows how, in the winter months, and due to the heavy demand for heating, the electrical production in rush hours

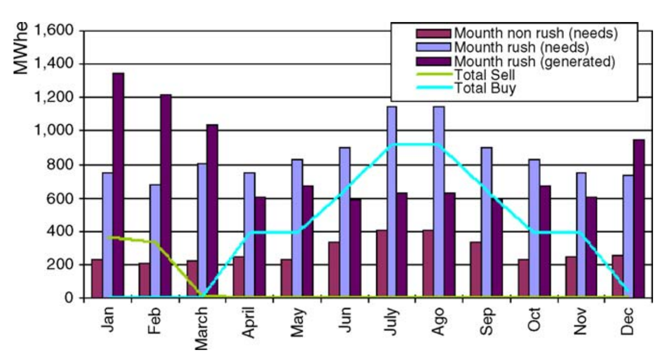

Fig. 3. Monthly electrical balance in MWh_e with two diesel engines of 2500 and 1500 kW_e.

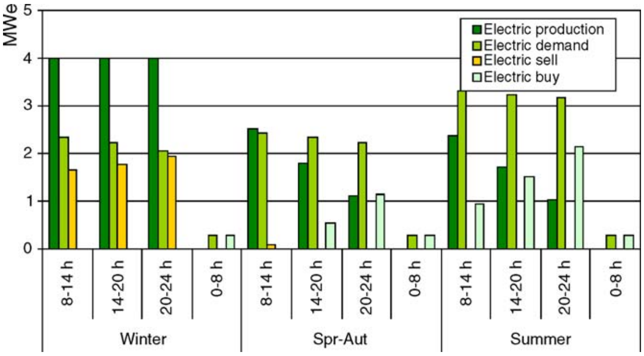

Fig. 4. Production, demand, buying and selling of electrical energy in workday rush hours with two diesel engines of 2500 and 1500 kW_e.

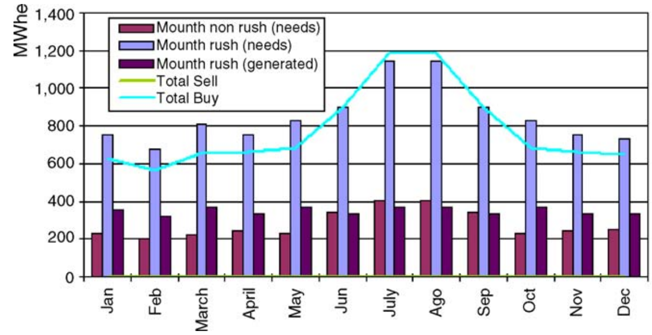

Fig. 6. Monthly electrical balance in MWh_e with a diesel engine of 1050 kW_e.

would be greater than the demand, whereas for the rest of the year it would be lower than the demand. In the non-winter periods, the thermal demand is quite low, and therefore the cogeneration would be working below its rated power. Globally, the system generates 70% of the hospital's total electrical consumption. Fig. 4 shows the annual distributions of production, demand, buying and selling of electrical energy in the hospital for workday rush hours.

5.1.2. Cogeneration with diesel engine and maximizing the use at full load

This second option, cogeneration with a diesel engine, considers the continuous operation of a 1050 kW_e engine at full load. The engine power is chosen based on the engine's thermal production, since it is this that will satisfy the minimum demand of the Hospital during the operating schedule of the cogeneration. The daily thermal demand and production for workdays and the monthly electrical demand and production are shown in Figs. 5 and 6.

The cogeneration works at full load during all the year, except in the nocturnal schedule and holidays, in which it remains shut down (see Fig. 5). The electrical production is quite constant all the year, at around 31% of the hospital needs, which is lower than that of the previous case (see Fig. 6). Fig. 7 shows the production, demand, buying and selling of electrical energy in workday rush hours. The hospital does not, at any time, export electrical energy to the network.

5.2. Cogeneration with gas turbine

The second of the proposed solutions is based on a gas turbine. The operating principle is similar to that of the diesel engines, though there are several differences:

- Although the global yield of the gas turbine is slightly superior to that of the diesel engine, 86–84%, the distribution between the thermal and electrical yields is very different: for a gas turbine 55.5 and 30.5% have been considered, respectively [6–8].
- Another aspect is that in the turbines the heat can only be recovered from the exhaust gases and there is no refrigeration of the turbine.
- The gas turbine has a low yield at partial load. For diesel engines, the yield is far greater in that situation.
- In the case of gas turbines, for small powers, the price per installed kilowatt of the cogeneration becomes excessive, while, at the same time, the electrical yield decreases.

5.2.1. Cogeneration with gas turbine and maximum electrical production

For this alternative, a power generation of 3000 kW_e has been considered. In order that the cogeneration does not have to work at partial load, which would reduce the performance considerably, the power production has been divided between two gas turbines of 1850 and 1150 kW_e.

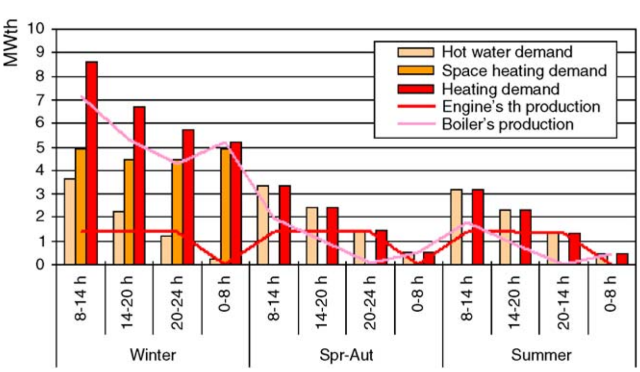

Fig. 5. Daily thermal balance in MW_{th} during workdays with a diesel engine of 1050 kW_{th}.

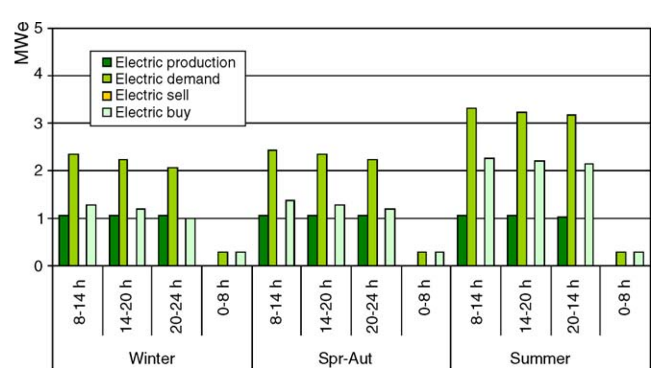

Fig. 7. Production, demand, buying and selling of electrical energy in workday rush hours with a 1050 kW_e diesel engine.

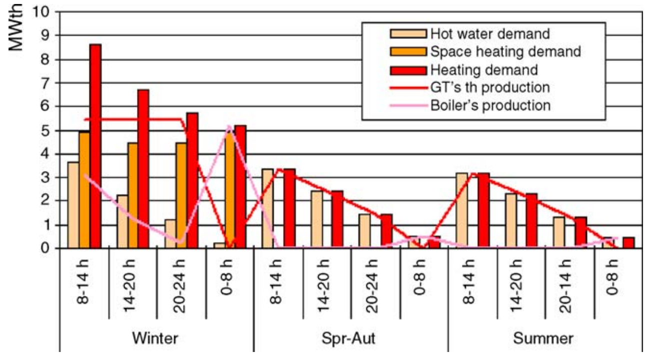

Fig. 8. Daily thermal balance in MW_{th} with two gas turbines of 1850 and 1150 kW_e.

Figs. 8 and 9 present the daily thermal balance in workdays, and the monthly electrical balance.

Fig. 8 shows how the cogeneration is able to cover a large part of the annual thermal demand. This type of cogeneration offers an improvement with respect to that offered by diesel engines due to the greater thermal production of the turbines in comparison with that of the diesel engines. As can be observed in Fig. 9, in winter months, due to heavy demand for heating, the electrical production would be higher than what is necessary, whereas the rest of the year it would be lower. Therefore, the cogeneration would have to work with one turbine stopped, and the other at partial load. Globally, 52% of the total electrical consumption is generated, quite inferior to the 70% obtained with the same design strategy but with diesel engines.

Fig. 10 shows the annual distribution of the production, demand, buying and selling of electrical energy for the hospital in workday rush hours.

5.2.2. *Cogeneration with gas turbine and full load use*

In this case, the cogeneration with gas turbines will work at full load most of the time, avoiding working at partial load. Thus, a single 1150 kW_e turbine has been considered. The heat balance in the working days and the monthly electrical balance are shown in Figs. 11 and 12.

This cogeneration system is able to cover only a small part of the thermal demand (see Fig. 11), despite working at full load all the year. The electrical production (see Fig. 12) is far lower than the previous case, providing just 32% of the hospital's needs. Fig. 13 shows the buying and selling of electrical energy

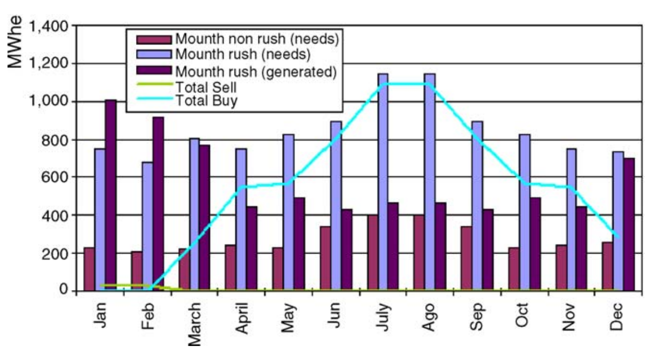

Fig. 9. Monthly electrical balance in MWh_e with two gas turbines of 1850 and 1150 kW_e.

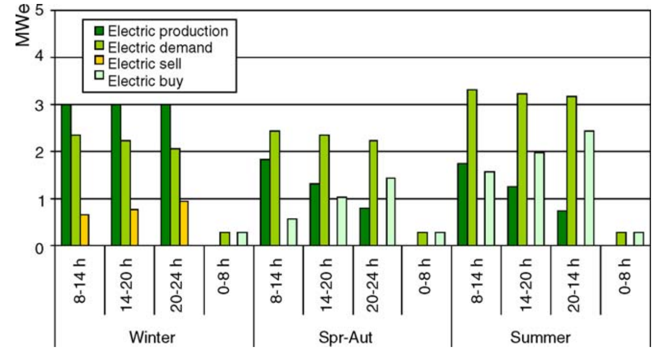

Fig. 10. Production, demand, buying and selling of electrical energy in workday rush hours with two gas turbines of 1850 and 1150 kW_e.

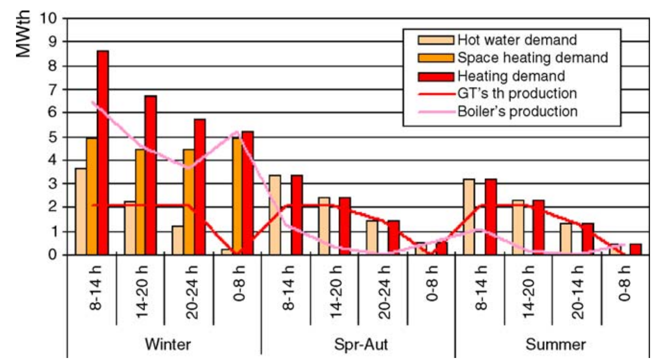

Fig. 11. Thermal balance in MW_{th} during the working days with a gas turbine of 1150 kW_e.

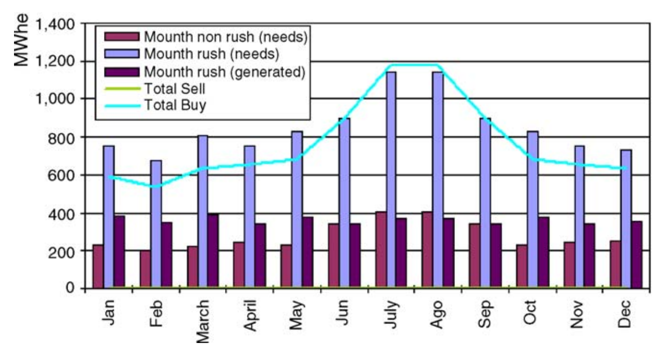

Fig. 12. Electrical balance with a gas turbine of 1150 kW_e.

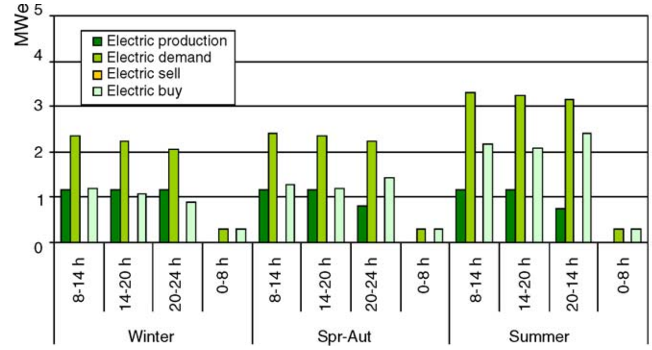

Fig. 13. Production, demand, buying and selling of electrical energy in workday rush hours with a gas turbine of 1150 kW_e.

in workdays, and it can be observed that the hospital does not, at any time, export electrical energy to the network.

6. Costs analysis

With respect to the installation and operation costs, and due to the number of different alternatives, a detailed economic study has not been carried out, but some general rules can be given concerning returns on investments.

Regarding the installation costs of the different alternatives, it has been decided not to consider the cost of the auxiliary boilers. The reason is that in each of the four options considered, the sum of the boilers' power is the same and equal to the reference installation. Thus, it has been considered that this value does not establish significant differences, since the only difference is the way in which the total power is distributed between the different boilers to cover the lack of heat from the cogeneration in the different periods at full load.

As operating costs, the totals per year have been considered, that is to say, the total costs of electricity and those of boiler fuels and cogeneration.

6.1. Installation costs

The installation cost has been determined considering various cogeneration projects carried out in Spain in which the government has collaborated IDAE [3]. The total installation costs of the different alternatives that have been considered are presented in Table 2.

6.2. Operating costs

The annual operating costs, classified in boilers, cogeneration and electricity; in the base situation and in the different alternatives considered, as well as the annual saving with respect to the base situation, are presented in Table 2. The economic study has taken into account an interest rate of 5%, and an installation working life of 10 years. The same table shows the yield, the cash flow and the investment required for each of the four alternatives studied.

The annual analysis of costs of all the studied alternatives shows that the cogeneration options with maximum electricity production present higher savings. No great differences are observed between the equivalent options of diesel engine or gas turbine.

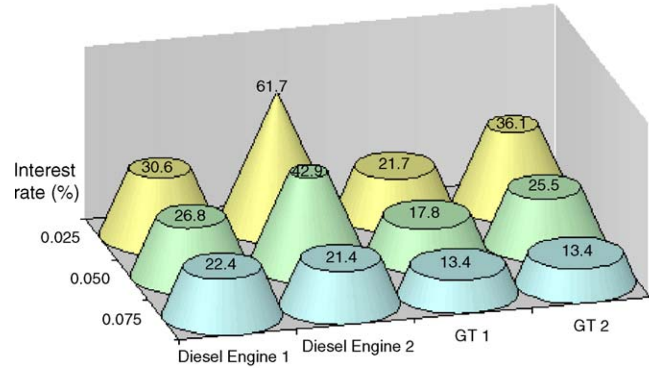

Fig. 14. Investment yield vs. the interest rate.

From the yield analysis, it can be deduced that the options with diesel engines are better than the equivalent ones with gas turbines, although the global yield of the turbines is greater than that of the engines. This is based mainly on two aspects:

- for small powers, as is the case of this study, the investment cost of the turbines is considerably greater than that of the engines;
- the performance of the facilities is strongly bound to the electrical production, and the production ratio of the engines is considerably greater than that of the turbines.

The investment that presents the greatest profitability is to use a diesel engine at the maximum electrical production, since operation at full load is the most frequent situation.

However, the option that produces the greatest total saving in money is cogeneration with diesel engine and maximum electrical production, since it is in this situation that the greatest amount of electricity is produced in rush hours, this being the most expensive energy.

In Fig. 14, the yield analysis of the four cases, considering three different interest rates, is observed. The options with diesel engine are better that equivalent ones with gas turbine, showing better yields the options that maximize the hours of

Table 2
Costs (€/1000)

Costs (€/year)	Base case	Diesel engine (1)	Diesel engine (2)	G.T. (1)	G.T. (2)
Facilities		3230	913.5	3737.5	1610
Boiler fuel	586	300	460	374	456
Cogeneration fuel	–	381	168	282	173
Buy electricity					
Peak	842	203	496	322	485
Valley	125	125	125	125	125
Sell electricity	–	118	–	49	–
Annual cost	1553	892	1249	1054	1240
Annual savings	–	662	304	499	314
Yield (%)		26.8	42.9	17.8	25.5

use at full load, although these are much more sensitive to the variations of this parameter.

Considering that this purchase price of the electricity in rush hours fluctuates within reasonable limits, it does not cause great influence on the yield.

In the cases where the production at full load is maximized, there is not sensitivity of the yield with the sale price of the electrical energy, since no energy is exported to the network. On the other hand, when maximizing the electrical energy production, this sensibility is not a relevant value; being higher with diesel engines than with gas turbines, since its installed power is also higher.

7. Conclusions

The work described in this paper has shown that any of the four proposed alternatives improves the current operating results. This conclusion should make great energy-consuming centers, such as hospitals seriously consider the possibility of implanting a cogeneration system. The economic resources of these centers could then be invested in the health service, and not in paying extra costs for the energy used.

Cogeneration presents other additional advantages, apart from the merely economic ones, since it reduces electrical disturbances in the power system, providing a more stable and safe operation of the set of electrical equipment of the hospital. In case of a severe failure in the network, the power station could provide, with the support of extra generation groups if necessary, electrical energy to the whole hospital, which is a guarantee given the special characteristics of the ‘‘client’’.

In addition, the way in which cogeneration power stations take advantage of the energy generated brings important environmental benefits. It should be noted that the global yield of a conventional thermal power station goes up to around 40%, which means that 60% of the primary energy (coal, petroleum, . . .) is not useful. In contrast, a cogeneration power station takes advantage of the residual thermal energy that is produced when generating electrical energy; that is to say, it needs to burn less fuel to produce the same amount of useful energy, the total losses being far lower, between 15 and 20%.

In the future, not only this type of power systems have to be considered, but also *trigeneration* with cold water production machines by absorption, especially in the countries of the south of Europe, where refrigeration requirements in summer are important. These facilities would allow the cogeneration to work at full load during longer periods of the year, and therefore contribute to an important improvement of the yield, since more electricity is produced.

In Spain, due to the widespread use of domestic air conditioning equipment, the maximum electrical demand has been transferred from the months of winter to summer, which is why *trigeneration* will contribute, not only to a greater economic yield of the facilities, but also to an unloading of the national infrastructure of generation, distribution and supply of electrical energy.

The final decision on the type of primary power source chosen is usually political and non-technical. For this consumer, the facilities with diesel engines are more profitable than with gas turbines. However, in Spain, in order to meet the Kyoto Protocol, the natural gas consumption is being supported as primary power source, since it is considered a clean energy. Nowadays, more than the 55% of the gas consumed in Spain comes from Algeria [9]; this makes very important to keep the supply in a suitable level avoiding possible failures. Any drop of the supply can cause the cogeneration system to be inefficient, and therefore a problem in the power provision to the hospital. On the contrary, the solutions with diesel engines allow the fuel storage by the client, and so, the reduction of the external power dependency.

Acknowledgements

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