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A case study of a cogeneration system for a hospital in Greece. Economic and environmental impacts

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HIGHLIGHTS

► The General Hospital of Piraeus “Tzaneio” as a candidate for the implementation of a cogeneration system is investigated.
► The annual operation hours of cogeneration system are examined.
► The effects of the consumption of fuel, the emitted pollutants and the level of economic indexes are investigated.

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ABSTRACT

The objective of the present work is to investigate whether a Hospital named “Tzaneio”, located in Piraeus, Greece, is a potential candidate for the implementation of a cogeneration system and also to determine the most suitable cogeneration system (electricity and heat). More specifically, after the presentation of the hospital’s energy consumption and the calculation of the energy consumption costs, alternative energy scenarios have been examined that propose the installation of cogeneration units of different power capacity for various profiles of operational hours. A comparative evaluation has been carried out for the selection of the most suitable CHP unit, following a specific procedure and taking into account a number of critical factors. The study showed that when the main gas engine (Diesel with natural gas) operates 8000 h/year and the backup unit 5000 h/year, the cogeneration system is most economically profitable. The total annual energy cost has been reduced by 32.4%. The Benefit-Cost Ratio (BCR) is greater than one, the Net Present Value (NPV) is positive and the Internal Rate Return (IRR) for 20 year lifetime of system is 19%. Also there is reduction of annual primary energy consumption by 28%, as well as a significant annual reduction of pollutant emissions.

1. Introduction

Hospitals have the highest energy consumption per unit floor area in the buildings sector [1]. The continuous use of heating and cooling equipment, in order to maintain satisfactory thermal comfort and indoor air quality levels for the patients as well as the use of artificial lighting on a continuous basis in several electrical health equipment, result in relatively higher energy consumption in comparison with other types of buildings [2].

From an energy audit campaign in the Hellenic health care buildings in the early 1990s, the average annual total energy consumption has been reported as 407 kWh/m^2 [2]. In another national investigation, the annual total energy consumption has been reported as 371 kWh/m^2 [3]. More recent data from ten hospitals in Athens [1] revealed an average annual total energy consumption of about 426 kWh/m^2. Significant variations of energy consumption may occur between different facilities, mainly due to differences in HVAC installations, since the majority of Hellenic hospitals is not fully air-conditioned (central HVAC is mainly used in new hospitals). For example, fully air-conditioned hospitals may reach annual energy consumption close to 700 kWh/m^2 [1].

There are a lot of studies dealing with the CHP in hospitals. The size of the facility and the control strategy has a strong influence on the CHP system economy, showing that the most important parameter is the electricity being produced [4]. The second law of thermodynamics may be used to develop a methodology in order to analyze cogeneration systems, based on exergoeconomics evaluation. The thermoeconomic optimization method developed is applied to allow a better configuration of the cogeneration plant associated to a university hospital [5]. In Brazilian hospitals the

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technical potential for CHP, around 500 MW, is the ceiling on the capacity that could be installed, providing that the systems are economically feasible [6].

Taking into account these high energy demands in Greek hospitals, it is beyond any doubt imperative that the implementation of cogeneration systems in these hospitals could prove very useful and many studies about the corresponding systems are carried out. In this study the viability and the economic, environmental aspects that arise from a CHP system's installation in a specific Greek Hospital of Piraeus, "Tzaneio", are examined.

2. Existing energy equipment

In this section the equipment that is used in the hospital in order to meet the needs of electricity, heat and air-conditioning is presented.

2.1. Heating loads coverage equipment

In the boiler room, which is placed in the basement of the old building, there are four boilers and two steam generators. Two of the boilers are larger, with a rated power of 1,000,000 kcal/h each, while the other two have a smaller capacity of 750,000 kcal/h each. The steam generators run on natural gas and have a total steam production of 2,000 kg/h. The exhaust gases are passed in and exported through a central chimney. The steam that is exhausted for the boiler is used for water heating and in the form of steam for washing machines, sterilization, operating rooms and kitchen facilities.

Kitchen: In this area the steam is consumed by a steam boiler with a heat output of around 150 kW with rated steam consumption of 200 kg/h (120,000 kcal/h).

Laundry: The steam washing machines and steam pressers have a heat power of 1,750 kW and rated steam consumption of about 2,500 kg/h (1,500,000 kcal/h).

Sterilization: The rated steam consumption for sterilizing is estimated at about 60 kg/h (36,000 kcal/h or 42 kW).

2.2. Cooling loads coverage equipment

The required cooling load for air-conditioning in the hospital is produced by 21 coolers with a total power of 1,200 kW. More specifically, there are 21 central cooling units, assisted by 261 split units.

2.3. Power distribution equipment

In order to meet the total electricity needs the medium voltage network of the PPC (Power Public Company), supplies the hospital through two substations. Moreover, as an additional backup there are five electric generators installed with a total power of 2,102 kVA. Two generators of 670 kVA each are placed in the new building, while two others of total 735 kVA are installed at the central building and one of 27 kVA is installed at the outpatient department. The electricity is consumed for lighting, mechanical power production, cooling, lifts, pumps, laundry, kitchen equipment, compressors, medical equipment machines etc. The basic electro-mechanical equipment mainly serves the kitchen equipment, the washing machines, the dryers and the air-conditioners.

Kitchen: The required electric power to meet the needs of appliances (ovens, pans, mixers, refrigerators, cooking machines) is estimated at 400 kW_e.

Laundry: The total rated wattage of the washing machines amounts to around 200 kW_e.

Medical equipment: Medical equipment characterized by high electrical power includes: Magnetic Resonance Imaging (MRI) scanner (120 kW_e), Computed Tomography (CT) scanner (100 kW_e), Medical imaging machines (250 kW_e) and other laboratory equipment (100 kW_e).

3. Energy consumption data

This piece of information is of great importance in order to find out the energy demand of "Tzaneio", the energy cost of the current conventional system and its environmental implications. Bills from the PPC and natural gas utility were used to meet this purpose.

3.1. Electricity consumption

Fig. 1 shows the monthly average fluctuations in electricity consumption of the hospital in kWh_e for the period 2007–2008.

We can see that the consumed electric energy during the summer period is greater than the energy consumed during the winter period. This is due to the increased need for space cooling during the summer months. The annual consumption of electric energy is 6957 MWh.

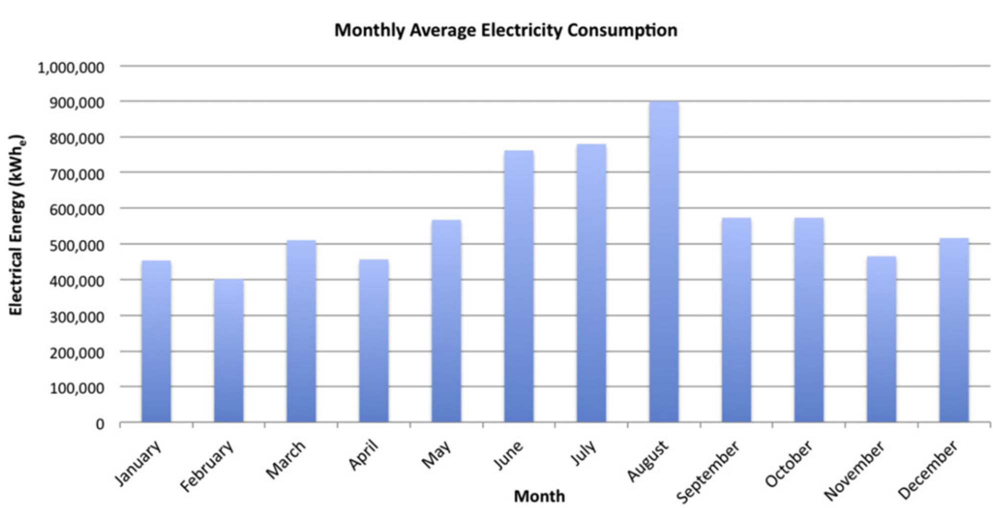

Fig. 1. Monthly average electricity consumption of the hospital in kWh_e for the period 2007–2008.

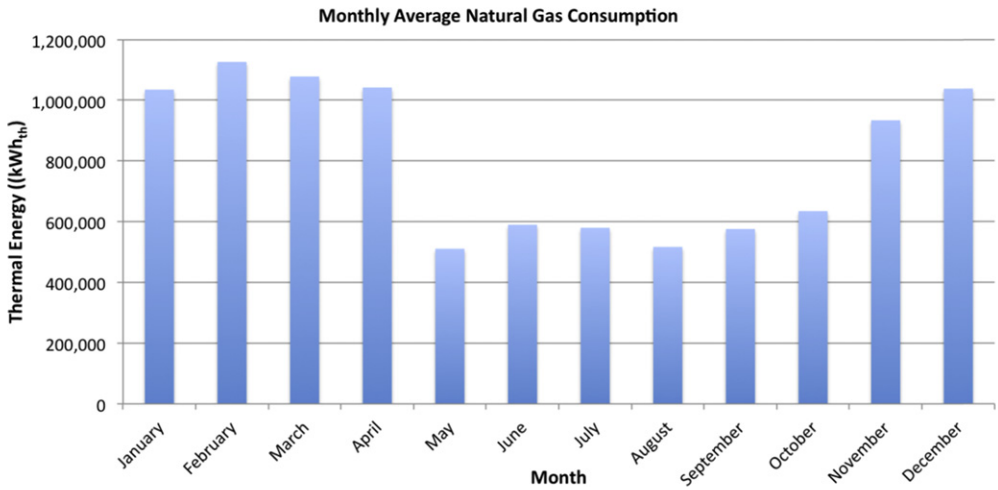

Fig. 2. Monthly average natural gas consumption in kWh$_{th}$ of the hospital for the period 2007–2008.

3.2. Natural gas consumption

In order to cover the heating load, the thermal power equipment, described in the previous section, is operating using natural gas as fuel. The analysis of the monthly natural gas consumption is based on the tariffs of the supplier for the years 2007–2008. Fig. 2 shows the monthly average values of natural gas consumption in kWh$_{th}$ of the hospital. The annual consumption of thermal energy is 9662 MWh.

As we can see in the above Figures, unlike the power consumption, the natural gas consumption is maximized during the winter because of the hospital's heating needs. The average ratio of electrical energy to thermal energy (PHR) can be estimated and for the particular facility, it is 0.72.

3.3. Cost for covering the energy needs by the existing energy systems

In order to calculate the costs of meeting the energy needs of the hospital using the existing equipment, the current prices of the PPC and natural gas invoices were used.

Table 1 shows the cost per month for covering the electricity needs on the basis of existing equipment, by taking into account that the current power value is 12.064 €/kW and the energy value is 0.07185 €/kWh [7].

Table 2 shows the cost per month for covering the thermal needs on the basis of the existing equipment, by taking into account that current average cost of natural gas is 0.055015 €/kWh [8].

Therefore, the annual energy and maintenance costs in order to meet the energy needs of the hospital, by using the existing energy equipment, are:

Annual electric energy cost	664,498 €
Annual thermal energy cost	531,555 €
Maintenance cost (assumed by hospital's technical service)	50,000 €
Total energy cost	1.25 million €

3.4. Environmental impacts from the existing conventional energy system

The air pollutant emissions and the primary energy consumption are calculated by using the collected data. These values of pollutants were considered along with the cost of meeting energy needs as a base scenario for the application of cogeneration. The electricity consumed by "Tzaneio" hospital results in the emission of pollutants from central power stations. Moreover, fuel consumption in the boiler in order to cover the thermal needs results in emission of pollutants locally. The basic parameters that have to be taken into account in the calculations are the following:

- The heating system efficiency, including gas boilers efficiency and distribution losses, according to the information provided by the technical department of the hospital, is about 85%.
- The typical efficiency of lignite-fired power plants in Greece is about 33% [9].
- Greenhouse gas emission factors are presented in Table 3.

Using the emission rates presented above and the electricity and fuel consumption calculated previously, Table 4 can be created.

Finally, the primary energy consumption is obtained by taking into account power and thermal consumption along with the boilers and central power stations efficiencies.

- Primary electric energy consumption (including cooling):

$$6957\ \text{MWh}/0.33 = 21,082\ \text{MWh/year}$$

Table 1
Cost for covering the electricity needs with the existing energy equipment.

Month	Debit maximum demand (kW$_e$)	Power cost (€)	Electricity consumption (MWh$_e$)	Energy cost (€)	Total electric energy cost (€)
January	864	10,423	453	32,548	42,971
February	840	10,134	402	28,883	39,017
March	864	10,423	510	36,644	47,067
April	915	11,039	456	32,763	43,802
May	1167	14,079	567	40,739	54,818
June	1569	18,928	762	54,750	73,678
July	1629	19,652	780	56,043	75,695
August	1548	18,675	900	64,665	83,340
September	1371	16,540	573	41,170	57,710
October	1086	13,102	573	41,170	54,272
November	942	11,364	465	33,410	44,774
December	852	10,279	516	37,075	47,354
Total cost					**664,498**

Table 2
Cost of natural gas used for covering the thermal needs with the existing energy equipment.

Month	Useful thermal energy consumption (MWh_{th})	Total fuel cost (€)
January	1035	56,940
February	1126	61,947
March	1078	59,306
April	1042	57,325
May	511	28,113
June	590	32,459
July	580	31,909
August	517	28,443
September	576	31,688
October	635	34,935
November	934	51,384
December	1038	57,106
Total cost		**531,555**

- Primary thermal energy consumption:

$$9662\ \text{MWh}/0.85 = 11,367\ \text{MWh/year}$$

- Total primary energy consumption:

$$21,082 + 11,367 = 32,449\ \text{MWh/year}$$

4. Sizing of the cogeneration units

Depending on the value of the PHR (0.72), the currently available cogeneration systems, which approach this power to heat ratio of the hospital, are the reciprocating internal combustion engines. C. J. Renedo et al. studied different cogeneration alternatives for a Spanish hospital center and it should be mentioned that the solution with diesel engine is more efficient than the equivalent ones with gas turbine [4]. From these reciprocating gas engines, those that operate with natural gas are preferred.

In order to select the appropriate system, it is necessary to determine, at first, the annual operation hours. Due to lower electricity prices from PPC during the night, it is assumed, at this stage, that it is not beneficial the facility to work for 5 h during the night. Consequently, the proposed system will operate for 19 h per day or 7000 h per year.

The selection of the operation mode (heat match or electrical match) depends on the local needs of the network and obligations toward the consumers of electricity and heat. Generally, the first mode is the one offering the highest energy and cost efficiency for the CHP systems in both the industrial and building sector [10].

In our case a «Heat match» mode is selected i.e. the CHP unit sizing will be based on covering, in priority, all the thermal loads. If a system for full coverage of the electrical needs has been chosen, the electricity during the off-peak hours would exceed the limit of 20% of the produced electricity that can be sold to the PPC. Consequently, it is rather unlikely that such a choice would be cost effective.

Based on the calculated average thermal power, we are looking for two gas engines of adequate installed capacity to cover fully the thermal needs of the hospital, even if they operate at partial load, assuming that the one covers the base of the thermal load and the other will operate as a backup during peak loads.

The choice of two similar gas engines (Diesel cycle) is superior over one engine (with an installed electrical power equal to the sum of two identical), as it offers flexibility to the system and increases the reliability of the whole installation. Also, the two internal combustion engines of the same installed capacity outperform the two with different capacity, as the operation and maintenance are governed by the same characteristics [3]. From a manufacturer of such systems the engines performances for 100% and 75% of load have been assumed.

The process of sizing the cogeneration system is exploratory and thus two possible scenarios are discussed.

Scenario A: A system is chosen by taking into account the average annual heat load, and considering that it operates at 100% of its nominal power. Two gas engines at 50 Hz are chosen, of installed capacity of 600 kW_e electrical output ($2 \times 600\ kW_e = 1200\ kW_e$) and 750 kW_{th} thermal output ($2 \times 750\ kW_{th} = 1500\ kW_{th}$), operating at 100% of their nominal power.

Scenario B: A system is chosen by taking into account the average annual heat load, and considering that it operates at a partial load of its nominal power, having thus the possibility of meeting future loads. Two gas engines at 50 Hz are chosen, of installed capacity of 800 kW_e ($2 \times 800\ kW_e = 1600\ kW_e$) and 1008 kW_{th} ($2 \times 1008\ kW_{th} = 2016\ kW_{th}$), thermal output considering that they operate at 75% of their nominal power, and thus, having the possibility to meet future loads.

For the two scenarios mentioned above, three different cases of operational hours of the gas engines are examined (main and backup):

- 1st case, Fig. 3: the main gas engine operates 7000 h and the backup 4000 h per year.
- 2nd case, Fig. 4: the main gas engine operates 7000 h and the backup 5000 h per year.
- 3rd case, Fig. 5: the main gas engine operates 8000 h and the backup 5000 h per year.

Following, scenario A and especially the 2nd case are presented in detail. For each month, the generated heat and electricity are estimated and compared with the required ones by the hospital heat and electricity loads. Thus, the surplus or deficit in energy for each month is calculated, according to the energy requirements of the General Hospital of Piraeus. Tables 5 and 6 show the calculations of the produced heat and electricity by the CHP unit.

The values in the aforementioned tables resulted as follows:

- It is assumed that the energy requirements of the hospital are equal to the average energy consumption for the years 2007–2008.
- The thermal energy produced by the cogeneration system is obtained by multiplying the operational hours with the heat power of the cogeneration system.

Table 3
Emission coefficients per pollutant for the thermal and electric energy production by various energy systems [4,6,7].

Pollutant	Specific emissions for electricity production of a typical coal-fired power station in Greece (kg/MWh)	Specific emissions of gas-fired heat boilers (kg/MWh_{th} of useful heat)	Specific emissions of a gas-engine CHP system (kg/MWh_e of electric output)
CO_2	1.346	255.55	577.26
SO_2	2.8	0.01	0.032
NO_x	2.3	0.19	1.9
Solid particles	1	0.02	0.014

Table 4
Annual air pollutant emissions of the existing energy system.

Pollutant	Quantities emitted for electricity production in central power stations (kg/year)	Quantities emitted by natural gas combustion in hospital's boilers (kg/year)	Total pollution quantities emitted for the cover of hospital's energy needs (kg/year)
CO_2	9,364,122	2,469,124	11,833,246
SO_2	19,480	97	19,576
NO_x	16,001	1836	17,837
Solid particles	6957	193	7150

- The electricity generated by the cogeneration system is obtained by multiplying the hours of operation with the electrical power of the cogeneration system.
- The shortage of electrical (or heat) energy is obtained if we subtract the required electrical (or heat) energy by the hospital from the generated electrical (or heat) energy of the cogeneration system. If the result is positive, there is an energy surplus.

More specifically, for the operation of the main unit for 7000 h per year (583.33 h per month) and for 8000 h per year (666.67 h per month), the heat output is calculated. Then, the monthly energy difference (surplus or deficit) from the heat required for the hospital's needs is calculated and where a deficit is estimated, the operational hours of the backup unit are distributed, for 4000 or 5000 h per year depending on the percentage of deficit observed every month, without exceeding the operational hours of the main unit. The remaining hours are shared equally to the summer months when there is a surplus of thermal energy.

The results described above for the three examined cases are summarized in Table 7.

From the above results the following observations may be made:

- As it is expected, the observation of the excess electrical energy occurs mainly during the winter months, while the excess heat is observed mainly during the summer.
- The first case of operating hours (7000 the base unit and 4000 h/year the backup) does not seem to meet the hospitals needs as regards the electrical and thermal load.
- In the second and third case of operating hours, the demanded electric load is sufficiently satisfied and there are no large amounts of excess electricity. Alongside this, the heat load is covered to a substantial degree. The existing natural gas boilers can cover the deficit in thermal energy during some winter months.

Therefore, there is a further investigation of these cases below, using the results obtained. The total energy cost of operating a cogeneration system consists of the following specific expenses:

- Purchase cost of natural gas for the cogeneration unit.
- Purchase cost of natural gas for boilers (for the months characterized by a deficit of heat energy).
- Purchase cost of additional electricity (for the months characterized by a deficit of electrical energy).
- Maintenance cost.

If, from these costs, the revenues from the sale of excess electricity to the PPC that is not exceeding the 20% of the total electricity produced annually are removed, the energy cost of the installation is given in Table 7.

The values in Table 7 have been calculated as follows:

- The cost of natural gas for the cogeneration plant is calculated by multiplying the fuel's consumption with the price of natural gas for cogeneration per kWh (0.042 €/kWh).
- The cost of natural gas of the boiler for additional heat energy is calculated in the case where there is deficit thermal energy. It equals to:

$$\text{Cost of gas for boilers} = \text{Thermal energy deficit} \times \text{price for natural gas boilers per kWh } (0.055015€/\text{kWh})/0.85.$$

- In the case that there is a deficit of electricity, the hospital, in order to cover it, purchases electricity from PPC at

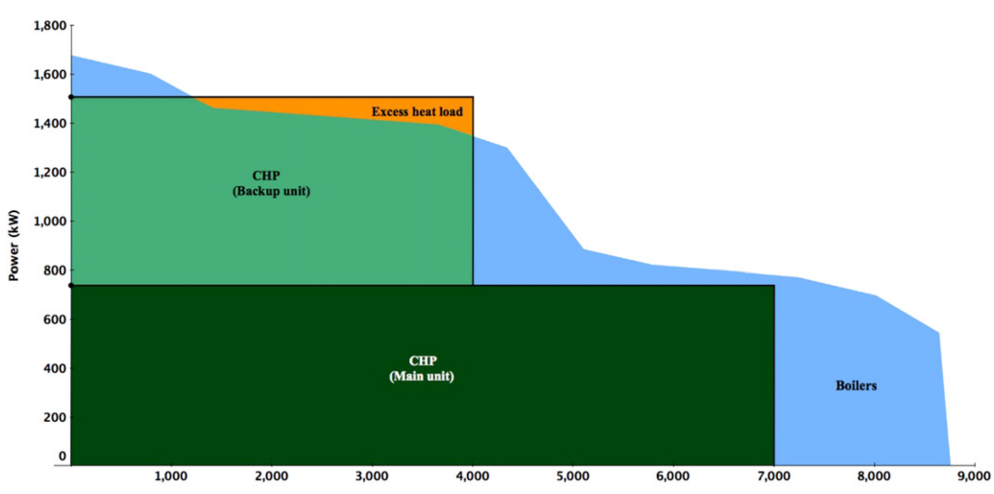

Fig. 3. Sizing of a cogeneration system using load curve (7000 h operation of the main unit and 4000 h operation of the backup unit).

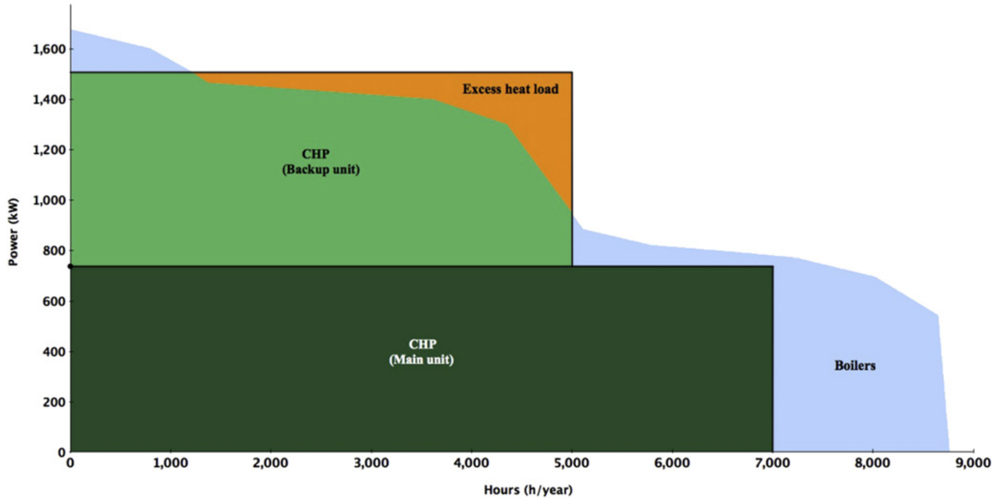

Fig. 4. Sizing of a cogeneration system using load curve (7000 h operation of the main unit and 5000 h operation of the backup unit).

0.07185 €/kWh (this price is an average that includes power and energy costs).

Actually, power would be purchased from PPC during a possible peak load that cannot be covered by the cogeneration unit.

- When there is a surplus of electricity, the hospital sells electricity to the PPC.

Revenues from the sale of surplus electricity equal to

electric energy $\times$ 0.08014 €/kWh.

- The maintenance cost is estimated as equal to 0.01 €/kWh electrical output [11].

In this case the total investment cost of the cogeneration system is investigated, as shown in Table 8.

The amounts in Table 8 have been calculated as follows:

- The cost of the cogeneration system includes all parts and accessories; appliances such as heat recovery boiler, generator and alternators of heat and exhaust gases. The cost of a CHP system driven by a gas-engine prime mover amounts to 850 €/installed electrical power (kW) [12].
- The replacement of the existing main boilers with new boilers burning natural gas includes the necessary accompanying equipment [3].
- The cost of connections and networks includes costs such as fees for connection to the natural gas network, heating and cooling networks, links with existing networks, etc.
- The various interventions and construction works arise from the installation of the system.

The evaluation of each case of operating hours as an investment scenario and the comparison with the current energy system is based on measures used for the evaluation of economic investments. These measures include Net Present Value (NPV), Benefit-Cost Ratio (BCR), Internal Rate Return (IRR) and the Simple Payback Period (SPB) [12,13]. With a market interest rate of 10%, evaluation period $n = 20$ years and including no lending, the results are shown in Table 9.

In order to further expand this study, the emitted pollutants after the installation of the cogeneration system are calculated (Table 10). It should be noted that the local emissions originate from the combustion of natural gas in the cogeneration system and the boilers.

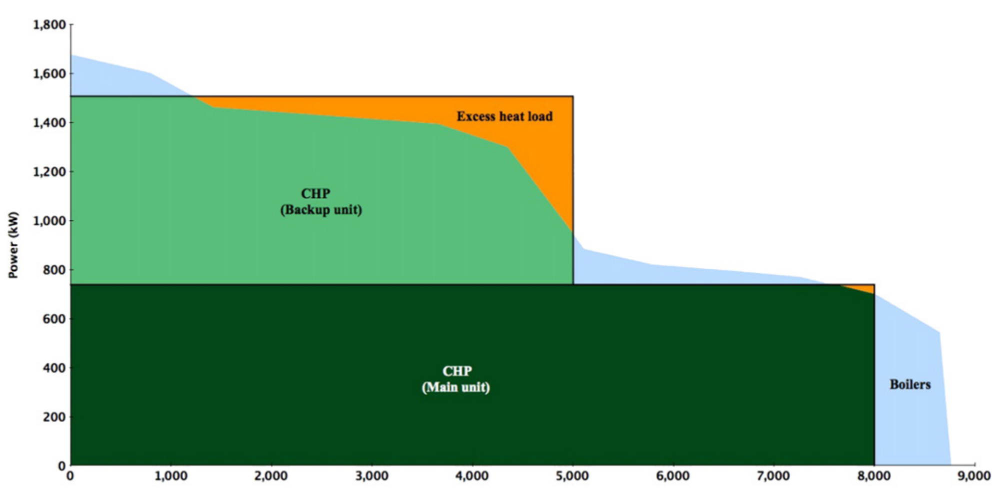

Fig. 5. Sizing of a cogeneration system using load curve (8000 h operation of the main unit and 5000 h operation of the backup unit).

Table 5
Generated thermal energy by system of two gas engines of installed capacity 600 kW$_e$ each that operate for 7000 h and 5000 h/year (2nd case).

Month	Useful thermal energy required (MWh$_{th}$)	Produced thermal energy (MWh$_{th}$) at 5000 h		Produced thermal energy (MWh$_{th}$) at 7000 h		Total thermal energy produced (MWh$_{th}$)	Deficit (−)/Surplus (+) (MWh$_{th}$)
		Hours	MWh$_{th}$	Hours	MWh$_{th}$		
January	1035	583.33	437.50	583.33	437.50	875.00	−160.00
February	1126	583.33	437.50	583.33	437.50	875.00	−251.00
March	1078	583.33	437.50	583.33	437.50	875.00	−203.00
April	1042	583.33	437.50	583.33	437.50	875.00	−167.00
May	511	223.67	167.75	583.33	437.50	605.25	94.25
June	590	288.06	216.05	583.33	437.50	653.55	63.55
July	580	279.91	209.93	583.33	437.50	647.43	67.43
August	517	228.56	171.42	583.33	437.50	608.92	91.92
September	576	276.65	207.49	583.33	437.50	644.99	68.99
October	635	223.82	167.87	583.33	437.50	605.37	−29.63
November	934	562.67	422.00	583.33	437.50	859.50	−74.50
December	1038	583.33	437.50	583.33	437.50	875.00	−163.00
Total	**9662**	**5000**	**3750**	**7000**	**5250**	**9000**	**−662.00**

Table 6
Generated electrical energy by system of two gas engines of installed capacity 600 kW$_e$ each that operate for 7000 h and 5000 h/year (2nd case).

Month	Useful electrical energy required (MWh$_e$)	Produced electrical energy (MWh$_e$) at 5000 h		Produced electrical energy (MWh$_e$) at 7000 h		Total electrical energy produced (MWh$_e$)	Deficit (−)/Surplus (+) (MWh$_e$)
		Hours	MWh$_e$	Hours	MWh$_e$		
January	453	583.33	350.00	583.33	350.00	700.00	247.00
February	402	583.33	350.00	583.33	350.00	700.00	298.00
March	510	583.33	350.00	583.33	350.00	700.00	190.00
April	456	583.33	350.00	583.33	350.00	700.00	244.00
May	567	223.67	134.20	583.33	350.00	484.20	−82.80
June	762	288.06	172.84	583.33	350.00	522.84	−239.16
July	780	279.91	167.95	583.33	350.00	517.95	−262.05
August	900	228.56	137.13	583.33	350.00	487.13	−412.87
September	573	276.65	165.99	583.33	350.00	515.99	−57.01
October	573	223.82	134.29	583.33	350.00	484.29	−88.71
November	465	562.67	337.60	583.33	350.00	687.60	222.60
December	516	583.33	350.00	583.33	350.00	700.00	184.00
Total	**6957**	**5000**	**3000**	**7000**	**4200**	**7200**	**243.00**

The primary energy consumption is calculated by adding the energy-fuel spent in the auxiliary boilers and cogeneration unit to the primary energy for electricity produced by central power stations, assuming that the average efficiency of the lignite-fired stations in Greece is 33%.

- Due to fuel combustion in the hospital's boilers:

$$\text{Deficit of thermal energy/efficiency boilers} = 1,048\ \text{MWh}/0.85 = 1,233\ \text{MWh}$$

Table 7
Energy cost of a CHP system with two-gas engines of 600 kW$_e$ each (running at constant load and equal to their nominal power) for the three examined cases.

Operation hours/year	7000 & 4000	7000 & 5000	8000 & 5000
Produced electricity (MWh$_e$)	6600	7200	7800
Total Surplus (MWh$_e$)	1247	1386	1954
Total Deficit (MWh$_e$)	−1604	−1143	−1111
PRODUCED THERMAL ENERGY (MWh$_{th}$)	8250	9000	9750
Total Surplus (MWh$_{th}$)	0.00	386	407
Total Deficit (MWh$_{th}$)	−1412	−1048	−319
FUEL CONSUMED (MWh)	16,518	18,020	19,522
Cost of natural gas for cogeneration plant (million €)	0.694	0.757	0.820
Cost of natural gas for auxiliary boilers (million €)	0.091	0.068	0.021
Cost of electricity purchased (million €)	0.115	0.082	0.079
Maintenance cost (million €)	0.066	0.072	0.078
Revenue from the sale of electricity (million €)	0.100	0.111	0.156
Total energy operating costs (million €)	**0.866**	**0.868**	**0.842**

Table 8
Investment costs of a CHP system with two gas-engines of 600 kW$_e$.

Cogeneration system cost (million €)	1.02
Replacement of boilers (million €)	0.50
Connections - Networking (million €)	0.30
Additional work - building works (million €)	0.20
Remuneration of consultants (million €)	0.08
Total investment (million €)	**2.10**

Table 9
Economic evaluation of the investment of a CHP system with two gas-engines of 600 kW$_e$.

	A-1 case	A-2 case	A-3 case
Total energy operating costs (million €)	0.866	0.867	0.842
Total investment (million €)	2.101	2.101	2.101
Energy cost savings (million €)	0.379	0.378	0.404
Net present value (NPV in million)	1.130	1.119	1.340
Benefit Cost Ratio (BCR)	1.5	1.5	1.6
Internal Rate of Return (IRR)	18%	18%	19%
Simple payback period (SPB) (years)	5.5	5.6	5.2

Table 10
Emitted pollutants after the installation of a CHP system with two gas engines of 600 kW_e.

Pollutant	Quantities emitted for electricity production by a coal-fired power station in Greece (kg/year)	Quantities emitted by natural gas combustion in CHP system (kg/year)	Quantities emitted by natural gas combustion in hospital's boilers (kg/year)	Total pollution quantities emitted for the cover of hospital's energy needs (kg/year)
CO_2	2,158,988	3,809,916	360,837	6,329,740
SO_2	4491	211	14	4717
NO_x	3689	12,540	268	16,497
Solid particles	1604	92	28	1725

- Due to fuel consumption in the cogeneration unit: 18,020 MWh
- Due to electricity from central power stations:

$$\text{Electricity deficit}/0.33 = 1,143 \text{ MWh}/0.33 = 3,463 \text{ MWh}$$

Therefore the primary energy consumption is 22,716 MWh.

Table 11 shows the primary energy consumption for the three examined cases.

5. Discussion

The existing setting of this study refers the current energy system in the General Hospital of Piraeus, Tzaneio. The research problem was to investigate whether there is any possibility of improving the energy performance of the current setting, using available cogeneration technologies.

Based on the information and all the data collected, the proper prime mover type and the correct number of the appropriate CHP units needed according to the candidate's load profile and the available CHP systems on the market have been examined in order to finally select the most appropriate. In order to obtain a complete and accurate picture of the economic and environmental advantages of the considered CHP implementation, the energy and GHG emission savings will be compared to the respective ones of the present conventional installation that covers the same loads.

This work performed a scenario divided into three different cases of operating hours. The first case does not meet hospital's needs for electricity and thermal energy while in the second and third case of operating hours, the demanded electric load is sufficiently satisfied and there are no large amounts of excess electricity. Alongside this, the heat load is covered to a substantial degree, while the excess heat, which occurs mainly during the summer months, can be converted to cooling through absorption chillers.

The annual cost for covering the hospital's electricity needs by the existing equipment, taking into account the current power and energy value (12.064 €/kW and 0.07185 €/kWh, respectively), reaches 664,498 €, while the annual cost of natural gas used for covering the thermal needs reaches the amount of 531,555 € (current cost of natural gas: 55.015 €/MWh). Taking into account that maintenance cost is 50,000 €, as reported by hospital's technical service, the total energy annual cost using the existing energy system is estimated to be 1.25 million €.

The total energy cost of operating a cogeneration system consists of the purchase cost of natural gas for the cogeneration unit, purchase cost of natural gas for boilers (for the months characterized by a deficit of heat energy), purchase cost of additional electricity (for the months characterized by a deficit of electrical energy), maintenance cost. If, from these costs, the revenues from the sale of excess electricity to the PPC are removed, at a rate that does not exceed the 20% of the total annual electricity produced, the energy cost of the installation seems that all the cases of this scenario lead to a reduction of annual energy operating costs up to 30.5%, 30.4% and 32.4% respectively and the payback period is 5.5, 5.6, 5.2 years.

Table 11
Primary energy consumption for the three examined cases in MWh.

A-1 case	A-2 case	A-3 case
23,040	22,715	23,262

As regards the environmental impacts from the existing system, total pollution quantities emitted reach 11,833,246 kg CO_2, 19,576 kg SO_2, 17,837 kg NO_x and 7150 kg of particles per year.

The total emitted pollutants (for electricity in central stations plus by the natural gas combustion in hospital's boilers and the CHP system) after the installation of a CHP system with two gas engines of 600 kW_e for the three cases of operating hours lead to a reduction of emitted pollutants per year. More specifically in all three cases we have a significant annual reduction of pollutants. CO_2 is reduced by 46.5%–48.6%, SO_2 by 75.9%–82.8%, NO_x by 2.3–7.5% and sold particles by 75.9%–82.9%.

The total primary energy consumption, calculated by adding the fuel spent in the auxiliary boilers to the primary energy for electricity produced by central power stations, is 32,449 MWh/year, regarding the existing energy system.

The primary energy consumption for all the examined cases leads to a reduction in primary energy consumption. More specifically, the 2nd case leads to a reduction of 9733 MWh/per year, i.e. to a percentage reduction of 30%, the 3rd case 28.3% and 1st case 29%.

Scenario B has not significant difference with scenario A compared with the reduction of annual energy operating costs, reduction of primary energy consumption and reduction of emitted pollutants per year. But there is a difference in the payback period that is respectively for the three cases: 6.4, 6.4 and 6.0 years.

6. Conclusions

Combined Heat and Power systems comprise a highly efficient method for the coverage of thermal and electrical needs in a single process. Hospitals are major candidates for such an implementation as they have high-energy loads throughout the year. The economic viability depends mainly on the appropriate sizing of the unit and the hours of operation, so that a substantial part of the hospital's energy needs may be covered and also the surplus of the electricity produced should not exceed 20% of the total electricity produced annually.

After the evaluation of the investment cases, being examined in this study, it emerges that the most attractive cases were the 2nd and the 3rd ones, which proposed that the main gas engine operates 7000 h/year and the backup 5000 h/year and that the main gas engine operates 8000 h/year and the backup 5000 h/year, respectively.

In both cases, the demanded electric load is sufficiently satisfied and the excess electricity produced lies within the limit of 20%; thus it can be distributed to PPC. Alongside this, the heat load is covered to a substantial degree, while the excess heat, which appears mainly during the summer months, can be converted to cooling through absorption chillers. From these two cases, the 3rd one is selected as the most economically profitable.

The total annual energy cost using the existing energy system has been estimated to 1.25 million € and this case led to its reduction by 32.4%. The economic evaluation demonstrated that it is a profitable investment since its BCR is greater than one, NPV is positive and the internal rate of return (IRR) for the 20 years lifetime of the system is 19%, so it exceeds the expectations of the investor. Moreover, the installation results in a significant reduction in annual primary energy consumption by 28.3%, as well as in a significant annual reduction of pollutants.

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