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The role of cogeneration systems in sustainability of energy

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ABSTRACT

Cogeneration system (CHP) is one of the ways to save the energy and use the energy efficiently. When compared to separate fossil-fired generation of heat and electricity, CHP may result in a consistent energy conservation (usually ranging from 10% to 30%) while the avoided CO_2 emissions are, as a first approximation, similar to the amount of energy saving. In terms of sustainability, one of the primary considerations is energy efficiency. Sustainable energy is considered as a kind of energy which is renewable and continuous, meaning that the use of such energy can potentially be kept up well into the future without causing harmful repercussions for future generations.

In this study, environmental benefits and sustainability aspects of cogeneration systems and importance of those systems to the use of sustainable energy are underlined. To support this idea, first we have referred some scientific studies previously made on cogeneration systems and then we have used our own case study. The case study made on gas engined cogeneration system was applied for a hospital to show the sustainability aspects of cogeneration systems.

1. Introduction

Energy is essential to economic and social development and improved quality of life. Much of the world's energy, however, is currently produced and consumed in ways that could not be sustained if technology were to remain constant and if overall quantities were to increase substantially [1]. Although the reserve of energy resources in the world is tending to decrease, the amount of the energy needed by humanity is tending to increase. In addition, dependence of the humanity on using energy is increasing day by day due to the improving technology, rise in the life standards of people in the world. This situation is becoming the most important and essential issue of the world. In general, there are two ways to overcome this problem. One of them is to bring out and improve new and renewable energy sources such as solar or wind energy systems. The other way is to improve conventional energy converting systems for using existing energy source more efficiently and for longer time, such as cogeneration systems. In other words, people have to do their best to improve the sustainability of the energy resources.

Although cogeneration is an old and proven energy conversion system, in recent years a resurgence of interest has come into world of energetic issue because of the energy crisis that has taken part in dockets of the countries in the world. Cogeneration systems and district heating/cooling applications offer us some proven, reliable, applicable and cost effective solutions which make very important contributions to meet global heat and electricity demand. Because of energy supply efficiency, use of waste heat and low carbon renewable energy resources of those systems, they are an important part of greenhouse gas emission reduction strategies of the countries in the world. Cogeneration is the simultaneous production of power and usable heat by using one type of energy source such as oil, coal, natural gas, liquefied gas, biomass or the Sun. In most of the cogeneration applications, the energy types produced simultaneously are electric and heat energy. Generally, those systems utilize the waste heat energy produced during electricity generation [2]. As a result, less fuel is required to produce a given amount of electrical and thermal energy in a single cogeneration unit than needed to generate the same quantities of both types of energy with separate, conventional technologies. Cogeneration systems have some significant advantages due to their environmental aspects. That is to say, the increase in efficiency and corresponding decrease in fuel use by a cogeneration system, compared to other conventional processes for thermal and electrical energy production, normally yield large reductions in greenhouse gas emissions. These reductions can be as large as 50% in some situations [3]. Cogeneration systems have economic advantages in many situations relative to separate processes for thermal and electrical energy production. The costs for cogeneration and non-cogeneration options are similar, but the other advantages (less fuel use and greenhouse gases) can still make the cogeneration system to be preferred [4].

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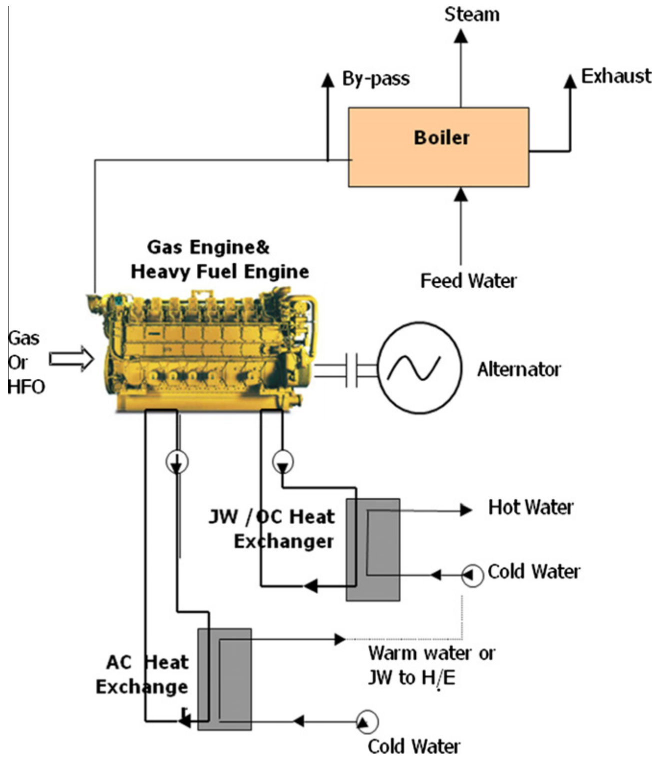

Fig. 1. Typical packaged internal combustion engine based (spark ignited) cogeneration system [21,22].

Sustainability is a necessity to make sure that we will have the capability to get the materials and resources which we need to protect human health and our environment. In a more general expression, sustainability is based on a simple principle: everything we need for survival and well-being, either directly or indirectly depends on protecting our natural environment. Sustainability creates and maintains the conditions under which humans and nature can exist in productive harmony that permit fulfilling the social, economic and other requirements of present and future generations.

Ecology means how biological systems remain diverse and productive over time. For humans, sustainability is the potential for long-term maintenance of well-being, which has environmental, economic, and social dimensions, and encompasses the concept of stewardship, the responsible planning and management of resources [5]. Sustainability has become a wide-ranging term that can be applied to almost every facet of life on Earth, from local to a global scale and over various time periods. Invisible chemical cycles redistribute water, oxygen, nitrogen and carbon through the world's living and non-living systems, and have sustained life since the beginning of time. As the Earth's human population has increased, natural ecosystems have declined and changes in the balance of natural cycles have had a negative impact on both humans and other living systems [6,7].

The terms sustainable and sustainability are used to describe many different approaches toward improving our way of life. Sustainability does not have a rigid definition. Sustainability means renewing resources at a rate equal to or greater than the rate at which they are consumed. In environmental terms, sustainability implies that an action can be continued indefinitely with little, or manageable, impact on the environment. Because the health of the environment is closely linked with the health of society in general, sustainable practices ensure that the Earth's resources will be available for future generations to enjoy, and that there will be an Earth to enjoy them on. For this reason, many scientific studies focus on sustainability, either as consultants to other companies or as part of their corporate mission [8].

In this study, environmental benefits and sustainability aspects of cogeneration systems and importance of those systems to the use of sustainable energy are underlined. To support this idea, first we have referred some scientific studies previously made on cogeneration systems and then we have used our own case study. The case study made on gas engined cogeneration system was applied for a hospital to show the sustainability aspects of cogeneration systems.

2. Sustainable energy and cogeneration

Generally, sustainable energy is considered as a kind of energy which is renewable and continuous, meaning that the use of such energy can potentially be kept up well into the future without causing harmful repercussions for future generations. A number of types of energy can be thought of as sustainable, and many governments promote the use of sustainable energy and the development of new types of energy generating technology which fit with this model. Increase in the rates of energy consumption all around the world have led to a corresponding rise in concerns about where this energy comes from.

Several factors are effective on making energy sustainable. The first is whether or not the current use of the energy is something which could potentially persist into the future, which leads many

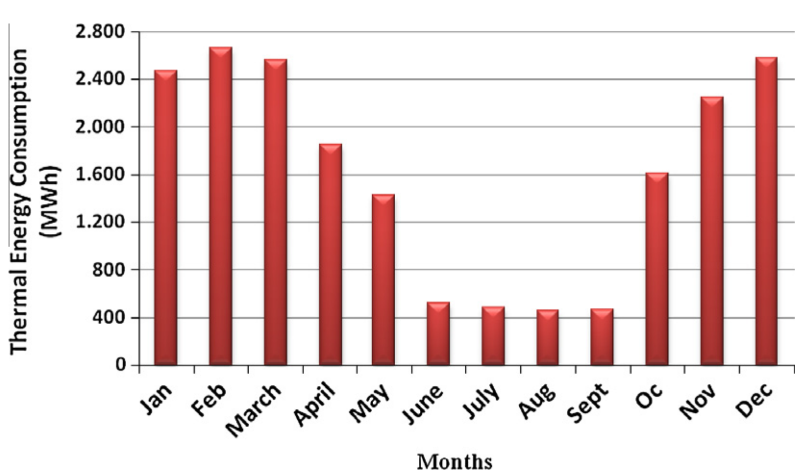

Fig. 2. Monthly thermal energy consumption of Aziziye Hospital throughout a year.

forms of renewable energy to be qualified as sustainable. People can generate energy from windmills, waves, and the Sun without consuming energy and resources. By contrast, fossil fuels are not treated as sustainable because the Earth's supplies of crude oil will eventually peter out.

In terms of sustainability, energy efficiency is another primary consideration. Some forms of renewable energy, for example, are sustainable in one sense, but researchers have yet to achieve a high level of energy efficiency, meaning that for utilizing such types of energy, much more energy has to be consumed. Increasing the energy efficiency is a vital way to make sustainable energy stretch further [8].

From this perspective, cogeneration systems can contribute to the sustainability of energy in two ways. One of them is to use cogeneration systems together with some renewable energy conversion systems like solar systems or heat pumps. This way can be thought as a first-hand application for sustainability. There are many studies on using cogeneration systems with renewable systems in the open literature [9–20]. One of them was made by Thilak Raj et al. [9]. as a review study on renewable energy based on cogeneration technologies. That paper reviews the present day cogeneration technologies based on renewable sources of energy. In addition, study of novel methods, existing designs, theoretical and experimental analyses, modeling and simulation, environmental issues and economic and related energy policies have been discussed in this study.

One of the energy conversion applications which are suitable for being used together or as a cogeneration system is solar energy system. Solar energy can be importantly utilized for cogeneration systems and various such technologies have been proposed. Using focusing collectors, solar energy can be converted in a central power plant to electrical energy which can then be utilized to operate a vapor compression refrigerator to produce cooling. At the same time, the waste heat rejected by the heat engine can be used to drive an absorption refrigerator. This system is simply called a solar powered cogeneration system for air conditioning and refrigeration and can play a dual role by saving energy and reducing the environmental pollution. Göktun [10] studied the solar power cogeneration system for air conditioning and refrigeration. By employing the energetic optimization technique, the optimal performance of a focusing collector-driven, an irreversible Carnot cogeneration system for air conditioning and refrigeration is investigated. A minimum value for the total solar insolation needed to overcome internal irreversibilities for start-up of the system is defined and the effect of the collector design parameters on this value is investigated. Hollick [11] made a study on solar cogeneration panels which investigated the method of combining photovoltaic cells with the transpired solar air heater, constructed prototypes, measured the combined electrical and thermal energies produced and compared the results with single function reference panels. The results showed that combining the PV cells with the transpired solar wall panels can produce higher total combined solar efficiencies than either of the PV or thermal panels on their own. Lindenberger et al. [12] presented an article on optimization of solar district heating systems; seasonal storage, heat pumps, and cogeneration which focused onto demonstrate the working of deeco in a pilot housing project of the Bayerische Forschungsstiftung (Bavarian Research Foundation). The quantitative results, i.e. the percentages of fossil fuels saved and emissions reduced with the help of different technology combinations at different costs, are specific to the pilot project. On the other hand, the qualitative interdependencies between energy conservation, emission mitigation and cost increases revealed by deeco are likely to be the same in all regional energy systems in moderate climates at the present level of energy prices.

The use of heat pumps (especially electric driven) has formed a new area of research. Heat pumps can be used together with cogeneration systems in some ways. Mancarella [13] proposed a novel approach to energy and CO_2 emission modeling of cogeneration systems coupled to electric heat pumps. The specific objectives were to identify the relevant parameters and variables involved in the analysis of such composite systems, and to provide a synthetic and indicative assessment of the energy and environmental benefits potentially brought with respect to conventional energy systems. The conditions at which energy and emission benefits occur, and their extent with respect to classical generation means, are illustrated through various numerical examples, highlighting the generality and effectiveness of the models introduced. A comparative parametric analysis was carried out in a small-scale combined heat and power plant incorporating a heat pump and the conventional system in which heat is produced in a hot water boiler and electrical energy is drawn from the power grid by Malinowska and Malinowski [14]. Relative exergetic efficiency is defined as the quotient of exergetic (rational) efficiencies of the cogeneration plant and the related conventional system. Dependence of this efficiency on the power-to-heat ratio for chosen values of parameters characterizing the compared systems is calculated and shown pictorially.

Biomass based cogeneration systems are becoming widely popular and various researches have been carried out in this area. In this part of the study some examples for such technologies are presented. Rafael Galvão et al. [15] presented the development of an energy model based on a mixed system of renewable energy, with primary energy sources as solar and biomass. It was a hybrid and autonomous system with solar PV panels and gasification cogeneration technology. Also it was an environment friendly process aiming to reduce the energy demand, costs and emissions. This energy model is a new sustainable standard about energy consumption efficiency (electrical and thermal demands) of a small hotel building and a relevant contribution to certify the building in compliance with the laws of the country on the thermal performance of buildings. Madlener and Bachhiesl [16] investigated the socio-economic drivers of large urban biomass cogeneration sustainable energy supply for Austria's capital Vienna. They provided a detailed case study on Austria's by far largest biomass cogeneration plant. They described and analyzed the history of the project, putting particular emphasis on the main driving forces and actors behind the entire project development process.

There are some other works in the literature on using cogeneration with different systems together to save more energy. In the study made by Burer et al. [17] and named as Multi-criteria optimization of a district cogeneration plant integrating a solid oxide fuel cell–gas turbine combined cycle, heat pumps and chillers; a simultaneous optimization of the design and operation of a district heating, cooling and power generation plant supplying a small stock of residential buildings has been undertaken with regards to cost and O_2 emissions. The simulation of the plant considers a super structure including a solid oxide fuel cell–gas turbine combined cycle, a compression heat pump, a compression chiller and/or an absorption chiller and an additional gas boiler. The Pareto-frontier obtained as the global solution of the optimization problem delivers the minimal CO_2 emission rates, achievable with the technology considered for a given accepted investment, or respectively the minimal cost associated with a given emission abatement commitment. Miller and Duffey [18] made a study on sustainable and economic hydrogen cogeneration from nuclear energy in competitive power markets. In that paper, they first put the energy demands of transportation in context. Next, the fluctuating price of electricity in an open market is used to cost distributed hydrogen production using electrolysis. Finally, the cost of electrolytic hydrogen is compared with other ways of supplying hydrogen to the dispersed vehicle market. Second one of the ways mentioned above which contribute to the sustainability of energy is to use conventional cogeneration systems. In contrast to the first way, conventional cogeneration systems which use fossil fuels (engined or with turbine) do not make a contribution to the sustainability directly, but they contribute indirectly by decreasing the emissions of greenhouse gases in production of energy by using fossil fuels and by offering efficient energy using. Overall cogeneration efficiencies based upon both the thermal and electrical energy production of 80–90% are achievable [19]. In other words, since combined heat and power systems involve the production of both thermal energy, generally in the form of steam or hot water, and electricity, the efficiency of energy production can be increased above 90% in the combined power systems while in the conventional power plants current levels of energy production vary from 35% to 55%. [20].

3. Case study

The sustainable energy discussions in this article are illustrated for the case of a natural gas fired cogeneration system at hospital. Cogeneration systems are designed depending on the energy needed primarily. The energy that is aimed to be generated primarily for hospitals is electricity since hospitals need for qualified electrical energy more than heating energy. The heat energy which comes into existence while electrical energy is being generated is used to meet the required thermal demands of hospitals, including hot tap water production, laundry and kitchen. The size of the system analyzed in this study is determined according to the maximum power demand of the hospital (Power demands in February as seen in Fig. 3) over a year by the help of catalogues of CAT engines.

3.1. Hospital description and data

Because of the critical importance of hospitals to people, their energy source must be continuous and best qualified. Therefore, the installation of a system for the simultaneous generation of electrical, heating and cooling energy would be the best solution if we want to have qualified energy and reduce investment and operating costs and meet ecological requirements at hospitals. Several studies were made on designing cogeneration systems for hospitals or other sites which are suitable for using those systems. They find out different cogeneration alternatives and different applying and designing methods for hospitals.

The Aziziye Hospital, the biggest and most prestigious hospital in Eastern Turkey, is located in Erzurum. Erzurum, with an altitude of 1853 m, is the coldest city in Turkey. The air temperature may decrease to −30 to −40 °C in winter. Spring and autumn seasons are very short in Erzurum and summers are warm but not hot. Heating systems are run in the mid-October and stopped at the end of May in Erzurum [21]. Energy consumption or energy demand of hospitals changes depending on official hours in day time and seasons or months during the whole year in Turkey. In day time, all of the medical devices and auxiliary equipments are in use and the number of patients is more than the night. There are two boiler systems at Aziziye Hospital, the first of these is steam boiler, which is used to meet thermal energy demands at the kitchen, laundry and hot tap water and the other one is red-hot water boiler which is used for heating hospital. Steam boiler is run from 07:00 to 19:00 every day during the whole year. Red-hot water boiler is run for 24 h a day from October to May in the year. The capacities of boilers are 5,000,000 kCal/h for red-hot boiler and 3,500,000 kCal/h for vapor boiler.

3.2. Energy demands of the hospital

The energy demand can be divided into two different types as thermal demand, consisting of space heating, hot tap water, cooking and drying room. The second type of energy demand of the hospital is electrical energy. Many air conditioning units are located in the administrative offices, doctor's offices as well as various laboratories at Aziziye Hospital but due to the climate conditions of the city, the wards do not contain air conditioning units at the hospital. In addition, as all operating rooms and intensive care units have specific room-temperature requirements and are thus equipped with autonomous air conditioning systems, the energy requirements of these environments are considered in electricity consumption. The hospital (herein referred to as consumer) in this study has an annual consumption of 19,334,437 kW h heat energy. To obtain this energy, the hospital consumes 2,016,104 m^3 of natural gas. Fig. 2 illustrates the thermal energy consumption profile of hospital over a year, calculated from the monthly bills.

Thermal energy demand of the hospital for space heating varies depending on the months of the year but the energy demand for other requirements does not depend on the period of the year but on time of the day. For that reason, the heat energy that is generated or recovered from the system will be used to produce hot tap water used at the kitchen, laundry and bathrooms. That is to

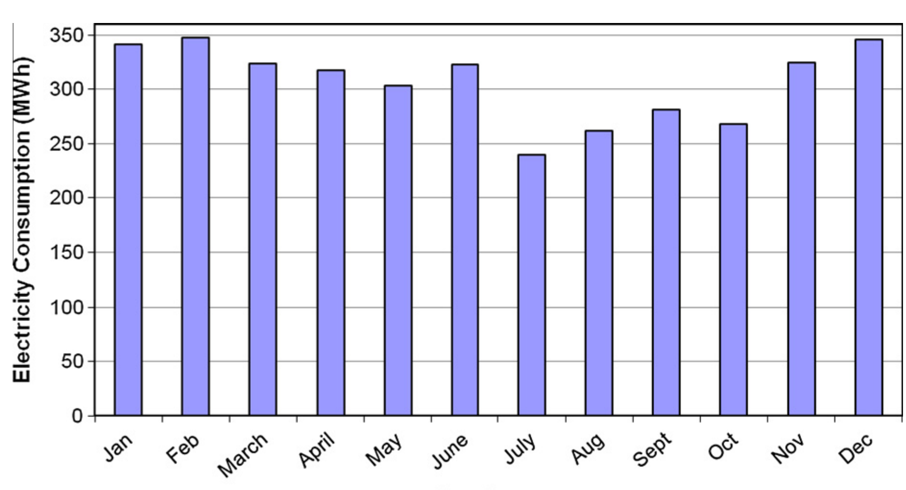

Fig. 3. Monthly electrical energy consumption of Aziziye Hospital throughout the year.

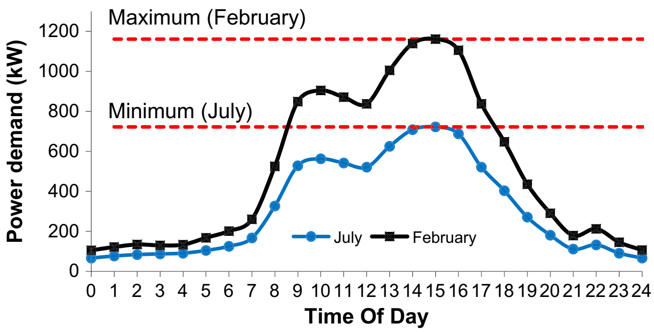

Fig. 4. Monthly electrical energy consumption of Aziziye Hospital throughout the year.

say, the heat energy gained from the cogeneration systems will be used during the whole year and benefitting rate of the cogeneration system will increase. Electrical energy consumption of the hospital is shown in Fig. 2 according to months in a year. As seen in Fig. 3, July is the month when minimum electrical energy consumption occurs and February is the month when maximum electricity is consumed.

Electrical demand of the hospital changes depending on the time of the day due to the changing working hours during the year. Fig. 4 shows the variant of electrical power demand of Aziziye Hospital depending on the time of day for July and February. As seen in the figure, maximum power need in a day occurred in February with 1161 kW and minimum one occurred in July with 722 kW during the whole year.

3.3. Gas engine cogeneration systems for hospital

In general cogeneration plants are classified either as topping cycle or bottoming cycle. Firstly the energy of fuel is converted to heat energy then it is converted to mechanical energy or transferred to working fluid to drive prime mover linked to power generators of cogeneration system to generate electricity. The remaining heat (waste heat) and the heat produced in prime mover are recovered for thermal processes in bottoming cycle. One of the most used prime movers of cogeneration systems is internal combustion engine which is operated according to Otto thermodynamic cycle. The basic elements of a reciprocating internal combustion engine based cogeneration system are the engine, generator, heat recovery system, exhaust system, automatic controls and acoustic enclosure. The generator is driven by the engine, and the useful heat is recovered from the engine exhaust and cooling systems [23]. The architecture of a typical packaged internal combustion engine based cogeneration system is shown in Fig. 1.

4. Results

In this section, for a natural gas fired engined cogeneration system at a hospital, the results of the analysis are presented and discussed here. To determine the power demands, we measured the electricity consumption of the hospital for each hour during 10 days for every month then we got the graphics of average daily power changes for every month similar to Fig. 4. According to these graphics, we reached the months which have maximum and minimum average daily power needs for the hospital. Depending on these demands, we selected the type of engine with 1656 kW mechanical capacities. Engine capacity was selected higher than demand because of the losses due to shaft (4%) and altitude factor. Efficiency of the system may decrease approximately 22% (0.78) because of the altitude effect in Erzurum (1853 m). Therefore,

Table 1
Specifications of G 3516 C engine.

Altitude (m)	500	1853
Engine power (100% load-kW)	1656	1291
Gen. power (100% load-kW)	1584	1240
Engine eff. (100% load-%)	40,8	
Thermal eff. (100% load-%)	44,5	
Total eff. (100% load-%)	85,3	
Engine speed (rpm)	1500	1500

maximum electrical power generation of the system will be 1240 kW [24]. General specifications of the engine selected from catalogues are shown in Table 1.

Efficiency of reciprocating engines changes depending on their running loads. For instance, when engine runs at full load (100%), the efficiency comes to 36.7% but when it runs at 30% load the efficiency comes to 31%. Accordingly, the engine will not be permitted to run under 50% load since low efficiency increases the cost of produced energy depending on increasing fuel consumption.

Due to the reasons mentioned above, we searched out about two running modes of cogeneration system for the hospital. One of them is running the system for supplying only hospitals' own electrical demands in different running loads from 50% to 100%. System will not run under 50% loads and when the system stops, the electrical energy will be obtained from the network. At this mode, the system will start when electrical demand of the hospital reaches 50% capacity of the engine and stop when it comes down the 50% capacity of the engine. So we determined the all running durations in different loads of the engine for different months of the year. Second mode is to run the system for 8000 h in a year at full load and sell the extra generated electricity to the electrical company. Cogeneration systems do not pose a problem in the case of producing more electrical energy than required for one's own consumption since Turkish law is suitable for 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 the first case of cogeneration, the engine will work in partial loads between 50% and 100%, in the times when demand of the hospital is equal or higher than the 50% capacity of the system during the year. In that case, the electrical energy produced by cogeneration system will be used only by the hospital and will not meet the total demand of the hospital in the whole year since the system will not work under 50% running load. As a result, the hospital will benefit from Network system to meet its demand for electrical energy during the rest of the day as seen in Fig. 5 and Table 2.

The heat and electrical energy balance of the system for that working case is shown in Table 3. As seen on the table, cogeneration cannot meet the total annual electricity demand of the hospital and some amount of electric should be bought from network. CHP unit does not work efficiently in this working case because of the efficiency decreasing fewer than 50% loads. Additionally, total annual heat and electrical energy demand of the hospital can be seen on that table. Annual energy consumption of the hospital is 3,676,441 kW h. Annual total heat energy demand of the hospital is 19,334,437 kW h and the hospital meets this thermal energy by using 2,016,104 m^3 natural gas. Although the cogeneration system does not run all over the year, big portion of electricity can be met by cogeneration. With this working case of cogeneration, nearly 68% of electrical demand can be met by cogeneration. Total natural gas consumption of the hospital has increased from 2,016,104 m^3 to 2,472,453 m^3 but if we handle the issue in a wider perspective, total energy using efficiency of the hospital has increased. Therefore, the energy resources used for the hospital have

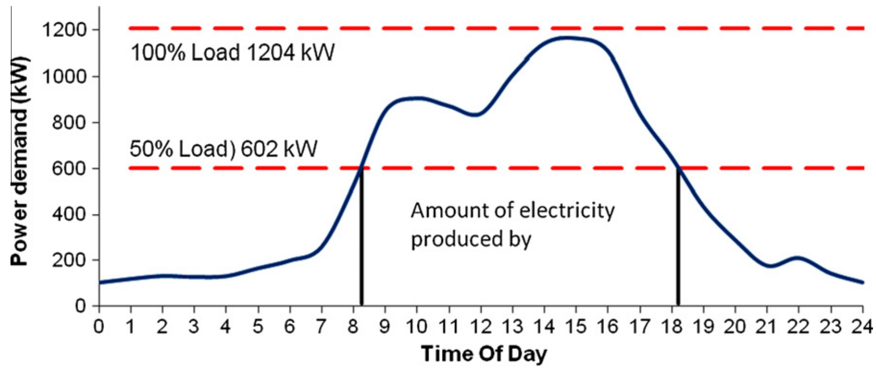

Fig. 5. Working situation of cogeneration system at different loads depend on the demand variety of hospital.

Table 2
Working properties of G 3519 C in first running mode.

Working load (%)	50–60	60–70	70–80	80–90	90–100	100	Total
Mechanic Power (kW)	828	993.6	1159.2	1324.8	1490.4	1656	–
Electric Power (kW)	602	722.4	842.8	963.2	1083.6	1204	–
Engine Efficiency (%)	38.3	39.72	39.74	40.24	40.52	40.8	–
Total working duration (h)	874.9	1023.6	574.6	429.6	72.8	0	2975.5
Produced Electricity (MW h)	601	831	538	456	87	0	2513
Gained heat energy (MW h)	533	710	444	367	675	0	1697

Table 3
Working conditions of system for first working case (2976 h/year at different loads).

Engine type	G 3516 C
Working time in a year (h)	2976
Running load (%)	50–100
Electricity	
Total demand (kW h)	3,676,441
Produced by CHP (kW h)	2,512,696
Obtained from network (kW h)	1,163,745
Heat	
Total demand (kW h)	19,334,437
Generated by CHP (kW h)	2,880,913
Generated from Boiler (KW h)	16,453,524
Gas consumption by CHP (m^3)	756,757
Gas consumption by boiler (m^3)	1,715,696
Total gas consumption (m^3)	2,472,453

Table 4
Working conditions of Cogeneration system for first running mode (8000 h/year at full load).

Engine type	G 3516 C
Working time in a year	8000 h
Running load (%)	100
Electricity	
Total demand (kW h)	3,676,441
Produced by CHP (kW h)	9,632,000
Used by hospital (kW h)	3,676,441
Sold to network (kW h)	5,955,559
Heat	
Total demand (kW h)	19,334,437
Recovered from CHP (kW h)	11,264,800
Generated by Boiler (KW h)	8,069,637
Gas consumption by CHP (m^3)	2,921,200
Gas consumption by boiler (m^3)	841,464
Total Gas consumption (m^3)	3,764,664

decreased. However, electrical energy that the hospital gets from network has decreased.

In the second case of cogeneration with gas engines CAT G 3516 C, the system will work in most of the year with 8000 h at full load, avoiding working at partial load. For that case, the heat and electricity balance in a year is shown in Table 4. Some amount of the heat energy will be met by the system and the rest of it will be produced by the conventional boiler system. In day time, all of the heat energy produced by cogeneration system will be used by the hospital. All of the electricity demand of the hospital will be met by cogeneration system for the whole year except for repairing time of CHP. In this case, the cogeneration system will produce the electric energy more than needed by the hospital. The big portion of the heat energy the hospital uses will be met by cogeneration system.

Total energy consumption of the hospital is 23,010,878 kW h (3,676,441 kW h for electrical and 19,334,437 kW h for thermal). As seen on the tables presented here, total natural gas consumption increases with cogeneration system, but the efficiency of energy conversion increases, too. In the first case (running under partial loads), total fuel consumption of the hospital has increased from 2,016,104 m^3 to the 2,472,453 m^3 with a difference of 456,349 m^3. In the second case (running under full load all over the year), total fuel consumption of the hospital has increased from 2,016,104 m^3 to the 3,764,664 m^3 with a difference of 1,748,560 m^3. Total efficiency of cogeneration system becomes 75% for the first running mode and 81% for the second one.

5. Conclusions

It is known that cogeneration systems are very important due to their technical efficiency, reliability and economical aspects for energy conversion applications. Since they provide with the primary energy savings and have high efficiency levels and decrease the greenhouse gas emissions, these systems make important contributions to the environment and nature. This efficiency also results in cost savings, reduces air pollution and greenhouse gas emissions, increases power reliability and quality, reduces grid congestion and avoids distribution losses. All in all, cogeneration systems contribute to the sustainable use of energy directly or indirectly in different ways with various application methods.

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