Article

Techno-Economic Performance Assessment of a Trigeneration System Operating in a Hospital

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Abstract: The techno-economic performance evaluation of a combined cooling heating and power (CCHP) system installed in a hospital building in Greece is presented. The aim was to verify performance standards and evaluate real behavior, while highlighting the economic gains. In this research, system performance was evaluated using actual and year-round field measurements. The data were used to calculate the recovered heat and the generated electric energy. Furthermore, the performance was modeled and compared to the manufacturer specifications. Financial assessment was conducted through energy cost analysis to verify the operating viability of the system, both for its heating and cooling functions. The results showed that, overall, after eight years of operation, the energy efficiency was still within design standards. Electrical efficiency was constantly above 30%, while thermal efficiency was around 40–45%. Total efficiency was usually above the 75% threshold, characterizing the system as fully CHP operating. The analysis also pointed out the economic effectiveness of the system in the Greek energy market. The results verified the potential of a CCHP system for improving the energy and economic performance of a building.

Keywords: CHP; CCHP; capacity factor; performance evaluation; key performance indicators; hospital; energy saving

1. Introduction

Combined heat and power (CHP) is defined as "the simultaneous generation of useful thermal energy and electrical and/or mechanical energy from the same initial energy, within a single process" [1]. The operation of the system in mechanical and energy terms has been extensively studied and explained in the literature [2]. A typical CHP system consists of an engine producing mechanical work to operate a generator, which converts the mechanical work into electricity, while a heat recovery system utilizes the waste heat to meet the thermal needs. The overall efficiency of the integrated system is thus increased from 30–45% to 80–85% [3]. In the case of trigeneration, an absorption chiller is added to the system to produce cooling energy.

The significant increase in efficiency offers economic and environmental benefits, including fuel savings and reduction of pollutant emissions [4]. On-site power generation eliminates transport and distribution losses, resulting in extra savings, while also protecting against electrical grid supply failures. The production of cooling can contribute to the unloading of the national electricity grid, deferring system investment costs [5]. Moreover, generated electricity can be sold to the grid, offering profit opportunities. The implementation of a CHP system as an energy saving application is in line with the objectives of protecting the environment and securing an energy supply, as is also mentioned in the Directive 2018/2001/EC of the European Parliament and of the Council, highlighting the necessity to take measures ensuring that cogeneration potential is further exploited [6]. However, some drawbacks still limit the widespread diffusion of such systems. Major disadvantages are the price volatility and the relatively high initial investment cost, especially when combined with weak financial supporting actions or administrative hurdles [7,8].

The success of the system is strongly related to the number of hours of operation [9]. Buildings of the tertiary sector, especially hospital buildings, have continuous energy demands daily and yearly, thus encouraging the application of CHP and CCHP systems, which has been a subject of research internationally [10–14]. CCHP has proven to be more effective in areas with warm climates, such as the Mediterranean region, where the need for heating might be limited to a few months during the year, but there is a significant need for cooling [4,15]. In Greece, several studies have investigated the implementation feasibility of trigeneration systems in hospitals [16–18]. In all examined cases, results show that total energy costs will be reduced while further economic and environmental benefits can be achieved from the use of natural gas; therefore, the implementation has been proven to be advantageous.

Performance assessment of CHP systems can be based on various criteria, such as technical, environmental or economic factors. Technical performance is analyzed in terms of energy production [19–21], or in other cases, in terms of power, based on the second thermodynamic law [22,23]. Environmental criteria can take the form of primary energy savings and reduction of emissions of gaseous pollutants [24], while the operating cost and the simple payback time are some of the main economic criteria [18,25,26]. A combination of the above is often chosen, increasing the complexity of the analysis [11,12,27].

Regardless the criteria, the accuracy of energy flow measurements is crucial for the evaluation. In most cases, the investigation is experimental, based on a system built and operating in a lab, which can be both expensive and time consuming [28–30]. As an alternative, detailed thermodynamic system models are created based on operating data from real systems [21,27], or simulation programs for dynamic analysis of energy behavior and building performance, coupled with mathematical optimization processes, are used to determine the energy loads and final performance of the system [31–33]. When no actual unit is available, the assessment is based on data provided by the manufacturer [27].

In only a few cases, data are from real systems, ones installed in an actual building and operating under normal conditions. Such a case is presented in [34], where several micro-CHP (5 KWe) units installed in small commercial buildings were being monitored to measure and evaluate their performance data. The data were compared to the manufacturer-stated performance and proven consistent. In [35], an existing CHP plant combined with district heating at the University of Perugia was analyzed in performance and economic terms using data from the first 15 months of operation. A cost–benefit analysis was performed after the first year of operation to optimize the performance based on the reduction of costs. Energy performance was the optimization criterion, as it is strongly related to financial benefit possibilities under the Italian legislation. The study [36] highlights the importance of conducting both the energy and exergy performance analysis of a CHP, to gain detailed insight into the system's performance and identify optimization possibilities. Efficiency results were compared to the system specifications. The electrical efficiency was proven to be in line with the manufacturer's standards, though the thermal efficiency was lower due to greater heat losses. Likewise, in [37], one of many biomass CHP district plants installed in South Tirol, Italy was being monitored to examine the performance under real operating conditions and compare it to the nominal one. Furthermore, a thermodynamic model calibrated with the experimental data was used for the identification of potential improvements by predicting the performance under different operation strategies. In [38], the challenge of optimally designing and operating a microCHP installed in a building, aiming to achieve the nominal efficiency under great fluctuation of heat and electricity demand, is discussed. The focus of the paper is mainly the part-load and start-stop behavior of different technologies of micro-CHP. The analysis was based on on-site measurement campaigns in the region of Flanders and results showed large discrepancies between the reported and actual efficiencies, highlighting the importance of the evaluation of real case studies. Lastly, research of that sort is presented in previous work of the authors [18], where the lifetime technical and economic performance of eight CHP projects operating in Athens is presented and evaluated, aiming to reveal the current situation of CHP in Greece

and identify factors hindering its penetration. The analysis used real operation data of the gas consumption since their installation. Results showed differences between the actual and the designed performances of the systems due to technical and economic reasons. The most successful cases were in a hospital and a hotel.

In this direction, this paper presents the technical and economic evaluation of a cogeneration system installed and operating in a hospital in Athens. Operation data are compared to manufacturer technical data and further used to determine the energy behavior under part-load operation. Energy cost analysis verifies the operating viability of the system, both for the heating and the cooling function. The evaluation of the performance is conducted by using three key performance indicators (KPIs): (a) the capacity factor (*CF*) and (b) the energy efficiencies—electrical efficiency n_e and thermal efficiency n_{th}—are used for the technical assessment, while (c) the cost of produced electricity $C_{e,chp}$ is used for the economic assessment. The technical assessment is expected to reveal possible deviations from the system's technical characteristics and the process design targets, while the economic assessment indicates the operating viability of the system.

Thus, the purpose of this paper is to verify the performance standards of an installed CCHP system and highlight its efficiency in terms of energy and cost savings potential.

2. Data and Methods

2.1. Technical Description

The cogeneration system is installed in a maternity clinic, located in an 11-floor building of 30,000 m^2 in Athens. The electric energy needs are covered through the national grid while two conventional boilers using natural gas cover the thermal needs. Here, a CCHP system was installed in June 2008, aiming to reduce energy costs. The system includes a 500 KWe electricity and thermal energy cogeneration unit with internal combustion engine (ICE) using natural gas, and a 629-KW cooling capacity single-effect hot water-fired absorption chiller. This was the first application of CCHP in a hospital in Greece.

The process flow sheet is presented in Figure 1. The generator produces electricity by combusting natural gas. The cogenerated heat is recovered through three circuits. Circuit 1 includes heat exchanger E3, which recovers heat from cooling the engine jackets, and heat exchanger E1, which recovers heat from the exhaust gases produced during combustion. Circuit 2 includes heat exchanger E4, which recovers heat through the cooling of the lubricating liquids and the intercooler, and circuit 3 includes heat exchanger E2, which recovers heat by further cooling the exhaust gases in the output of E1. Heating energy from circuit 1 is allocated to cover space heating or cooling and heating energy from circuits 2 and 3 is for water heating.

A flow meter (4–20 mA flow meter) is installed in each of the three circuits, and temperature sensors (PT100 for water and air sensors and TYPE-K thermocouple for gas sensors) measure the water temperature in the input and output of every heat exchanger. Flow switches are also installed to supervise the water flow. Temperature and water flow measurements are recorded every minute by a SCADA monitoring system. The meters necessary for the proceeding energy flow analysis are displayed in Figure 1.

A programmable logic controller (PLC) controls various parts of the sensor values system and gives the corresponding commands for operation and system security, according to the set points. If temperature reaches above a pre-specified limit or if there is low water flow detected, the engine enters an emergency operation mode.
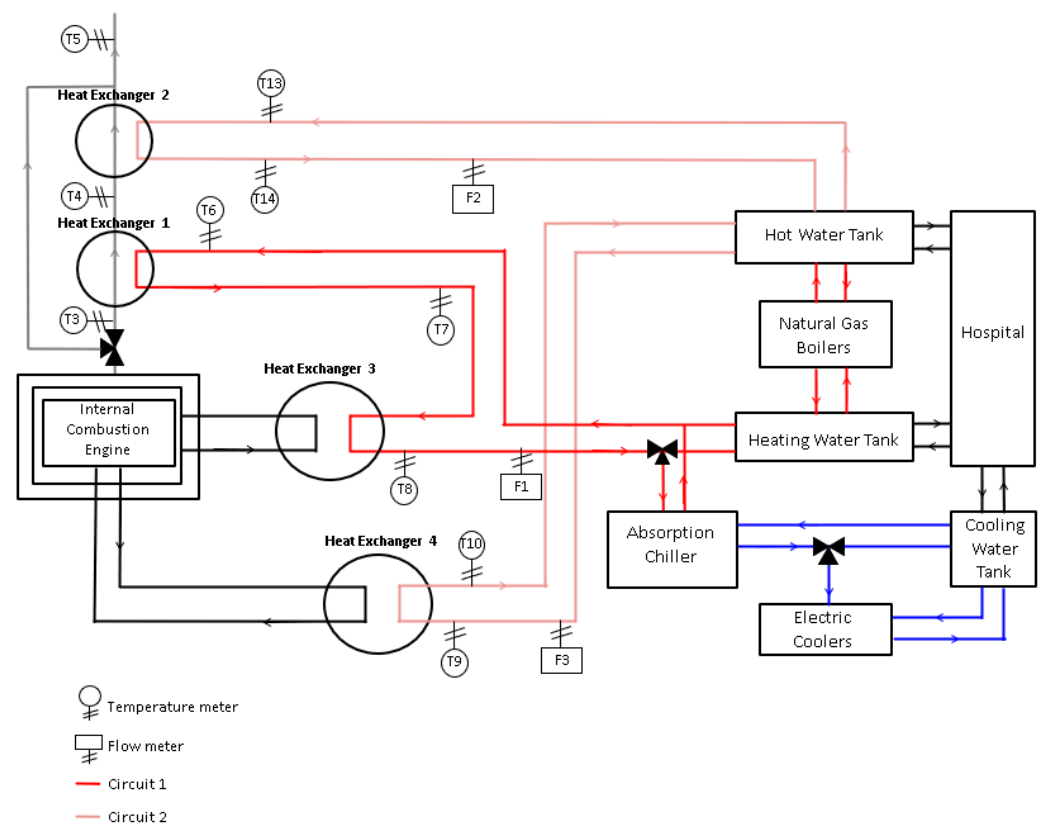
Figure 1. Process flow sheet of the CHP system installed in the hospital.

The produced electricity is consumed, and the cogenerated heat is used mainly for space heating and a small part for cooling. The operation follows the thermal load, as there is no thermal storage. During the heating period, all the recovered thermal energy is used for heating purposes. During the cooling period, the thermal energy from circuit 1 is transferred through the triode valve to the absorption chiller and used for cooling. The rest of the cooling needs are covered by electric chillers.

In terms of the conventional heating system, the water temperature in the water tanks trigger its operation. For the heating water tank, temperatures lower than 75 °C require the conventional boilers to work. For the hot water tank, the set point is at 55 °C. CHP unit operation is prioritized and supported by the conventional system.

From 2008 to 2013, the CHP unit was partly working. In December 2014, the CHP schedule was defined to operate on working days (Monday–Friday) during the hours of higher electricity prices (07:00 to 23:00). At the end of the heating season in 2015, due to satisfying economic results, it was decided to have continuous operation from Monday at 07:00 until Friday at 23:00.

2.2. CHP System Design Characteristics

The design characteristics, as defined by the manufacturer Waukesha, are summarized in Table 1 and presented in Figure 2.

Table 1. CHP system design characteristics.

Load	%	31	47	62	77	93	100	110
Power	KW	155	233	309	387	465	500	550
Fuel consumption	KW	558	737	917	1097	1276	1348	1463
Heat from Jacket Water	KW	207	243	279	315	351	365	388
Heat from Lube Oil	KW	32	34	36	37	39	40	41
Heat from Intercooler	KW	8	15	26	40	57	65	79
Exhaust Gas Flow	t/h	1.02	1.39	1.76	2.15	2.53	2.69	2.94
Exhaust Temperature after Turbine	°C	406	419	427	432	432	432	429
Total Energy from Exhaust Gas for Rejection at 25 °C	KW	131	182	236	290	342	362	392
Electrical Efficiency	-	0.28	0.32	0.34	0.35	0.36	0.37	0.38
Max Thermal Efficiency	-	0.68	0.64	0.63	0.62	0.62	0.62	0.62
Max Thermal Efficiency from Exhaust Gas	-	0.23	0.25	0.26	0.26	0.27	0.27	0.27
Max Thermal Efficiency from Engine Cooling	-	0.44	0.40	0.37	0.36	0.35	0.35	0.35
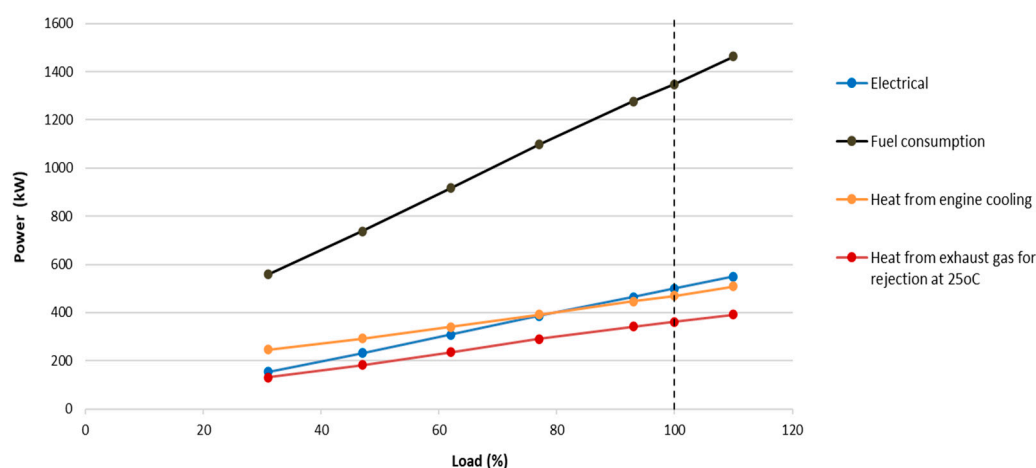
Figure 2. CHP system design characteristics in part-load operation.

2.3. Data Monitoring

The analysis covers a period of one year from July 2015 to June 2016.

Energy flows, generated electricity, and recovered heat are calculated based on measurements recorded by a SCADA monitoring system. Hourly natural gas consumptions are monitored by the Gas Distribution Company. Energy prices are selected through invoices from utility companies.

The following data are recorded in hourly values:

(1) E (kWh)   the electricity production;
(2) G (kWh)   the natural gas consumption;
(3) t (h)   the time of operation;
(4) F_1 (t/h)   the water flow rate in circuit 1;
(5) F_2 (t/h)   the water flow rate in circuit 2;
(6) F_3 (t/h)   the water flow rate in circuit 3;
(7) T_6 (°C)   the water temperature at the inlet of the heat exchanger E3;
(8) T_7 (°C)   the water temperature at the outlet of E3 and the inlet of E1;
(9) T_8 (°C)   the water temperature at the outlet of E1;
(10) T_9 (°C)   the water temperature at the inlet of E4;
(11) T_{10} (°C)   the water temperature at the outlet of E4;
(12) T_{13} (°C)   the water temperature at the inlet of E2;
(13) T_{14} (°C)   the water temperature at the outlet of E2.

In addition, the following economic data are selected through invoices in monthly values:

(1) C_g (€/MWh) the natural gas price for heating purposes;
(2) $C_{g,c}$ (€/MWh) the natural gas price for cogeneration purposes;
(3) C_e (€/MWh) the electricity price;
(4) C_m (€/MWh) the cost of maintenance.

The plant's monitoring system only records the CHP function; thus, assessing the function of the cooler and calculating its actual performance can only be done with on-site measurements. In this regard, the performance of the cooler function is not analytically examined in this research. The COP of the cooling system was measured from on-site measurements during one typical summer day. The achieved COP was 0.7.

2.4. Key Performance Indicators

Key performance indicators (KPIs) are fundamental indices for assessing the plant's operation. The CHP system is evaluated according to its technical and economic performance based on simple energy and economic balances. The key performance indicators used in the proceeding analysis related to technical performance are (a) the capacity factor (CF) and (b) the energy efficiencies—namely, electrical efficiency n_e and thermal efficiency n_{th}—while (c) the cost of produced electricity $C_{e,chp}$ was used to analyze the economic performance.

The capacity factor (CF) of a CHP system is an indicator of the full potential of the system compared to the current operation. It is defined as the ratio of its actual electricity produced E during the examined period to its potential production if it operated continuously and at a nominal power P_{nom}, and it is calculated according to the equation:

$$CF = \frac{E}{P_{nom}t'} \tag{1}$$

where t' (h) is the total hours of the examined period.

The recovered thermal energy in each heat exchanger Q_i is calculated from the flow rate and temperature difference of the fluid passing through.

$$Q_i = F_i C_p \left(T_{out} - T_{in} \right) \tag{2}$$

$$Q_1 = F_1 C_p \left(T_8 - T_7 \right) \tag{3}$$

$$Q_2 = F_1 C_p \left(T_7 - T_6 \right) \tag{4}$$

$$Q_3 = F_2 C_p \left(T_{14} - T_{13} \right) \tag{5}$$

$$Q_4 = F_3 C_p \left(T_{10} - T_9 \right) \tag{6}$$

where C_p (kWh/t) is the specific heat capacity of water.

The equation for the total recovered heat Q is:

$$Q = \sum Q_i = Q_1 + Q_2 + Q_3 + Q_4 \tag{7}$$

Efficiencies are calculated by the following equations:

$$n_e = \frac{E}{G} \tag{8}$$

$$n_{th} = \frac{Q}{G} \tag{9}$$

$$n_{th,g} = \frac{Q_2 + Q_3}{G} \tag{10}$$

$$n_{th,w} = \frac{Q_1 + Q_4}{G} \tag{11}$$

where n_e is the electrical efficiency, n_{th} is the thermal efficiency, $n_{th,g}$ is the thermal efficiency from exhaust gas, $n_{th,w}$ is the thermal efficiency from engine cooling, and G (kWh) is the natural gas consumption.

The avoided natural gas G_a and the avoided electricity consumption E_a are calculated as follows:

$$G_a = (1 - f) \frac{n_{th}}{n_b} G \tag{12}$$

$$E_a = f \frac{n_{th}}{COP_e} \frac{COP_a}{} G \tag{13}$$

where n_b (-) is the thermal efficiency of the conventional boiler, COP_a (-) is the coefficient of performance of the absorption chiller, and COP_e (-) is the coefficient of performance of the conventional electrical chiller.

In the above equations, f represents the part of the recovered heat that is used for space cooling, which is calculated as:

$$f = \frac{a \, (Q_1 + \ Q_2)}{Q} \tag{14}$$

where a is the part of recovered heat that is used for space cooling, with $a = 0$ for the heating period and $a = 1$ for the cooling period, and $Q_1 + \ Q_2$ (kWh) is the heat recovered in circuit 1 and used for space heating.

The cost of the electricity produced by the cogeneration system $C_{e,chp}$ is calculated from Equation (15). $C_{e,h}$ represents the cost when the recovered heat is used for space heating and $C_{e,c}$ represents the cost when the recovered heat is used for space cooling. In Equations (16) and (17), the first term relates to maintenance costs, the second refers to the cost of natural gas and the third refers to the savings from the conventional energy substitution.

$$C_{e,chp} = (1 - f) \, C_{e,h} + \ f C_{e,c} \tag{15}$$

$$C_{e,h} = \left(C_m + \frac{C_{g,c}}{n_e} - \frac{n_{th}}{n_e n_b} C_g \right) \tag{16}$$

$$C_{e,c} = \left(C_m + \frac{C_{g,c}}{n_e} - \frac{n_{th} \, COP_a}{n_e COP_e} C_e \right) \tag{17}$$

The condition for economic operation of CCHP is defined by comparing the cost of produced electricity to the cost of purchased electricity, following the approach by Tataraki et al. in [8]. The conditions for the heating and cooling modes, respectively, are:

$$C_e \geq C_{e,h} \tag{18}$$

$$C_e \geq C_{e,c} \tag{19}$$

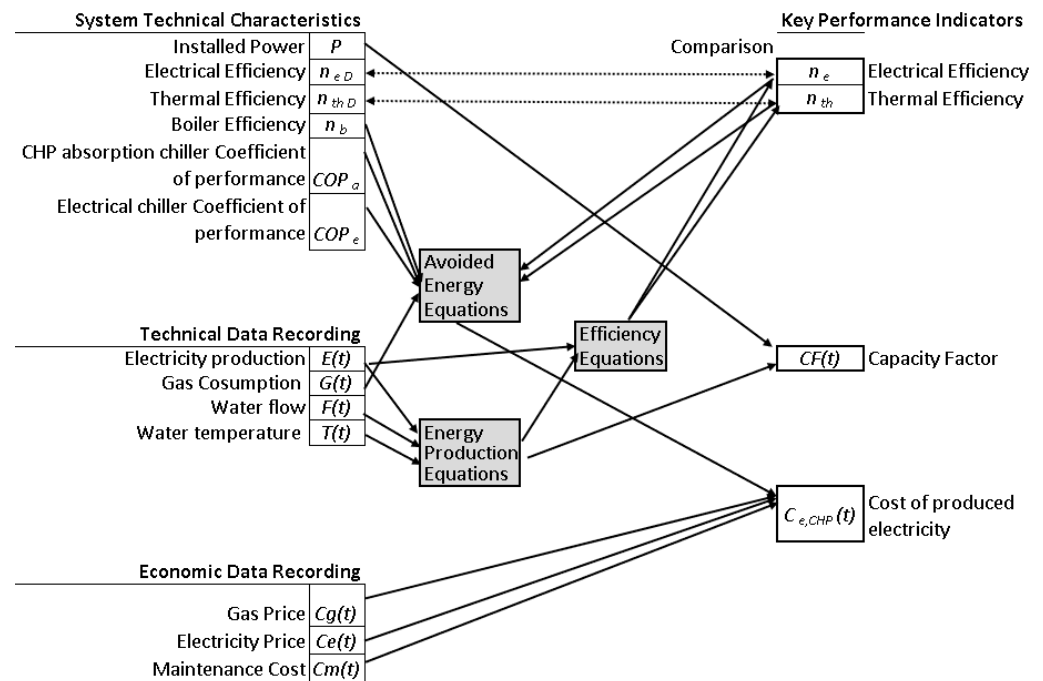The above analysis is summarized in the information flow diagram of Figure 3.

Figure 3. Information flow diagram of the selected key performance indicators (KPIs).

3. Results and Discussion

3.1. Monitoring Results

In Figure 4, the monthly total time of operation is presented. It is apparent that the CHP is not in constant operation, with the operating schedule covering 65% of the total examined period. The operating hours during the examined period are scheduled from Monday at 07:00 until Friday at 23:00.

Figure 5 presents the hourly values of the monitored temperatures for one typical day of the heating period and one of the cooling period. Temperatures present fluctuations, especially during the heating period. During the cooling period, temperatures in circuit 1 are higher. Flows are kept stable throughout the 24 h, so they are not presented graphically.

The monthly values of recovered heat in each heat exchanger are presented in Figure 6. Values are higher in circuit 1, including heat exchangers 1 and 3, designated for space heating. However, heat recovery in circuit 1 decreases after December (2015), and especially during the cooling period of 2016. The system should be designed to give priority to the CHP.

The monthly average values of all economic parameters are presented in Figure 7. In June (2016), the purchased electricity values are affected by the hospital's decision to switch to a different provider company. The feed-in tariff (FiT) applied by the Greek authorities to support CHP are also presented to economically analyze this scenario as well, although the energy is not sold to the grid. The FiT, according to the Greek legislation, is calculated monthly as a function of the average gas price to eliminate a gas volatility risk.
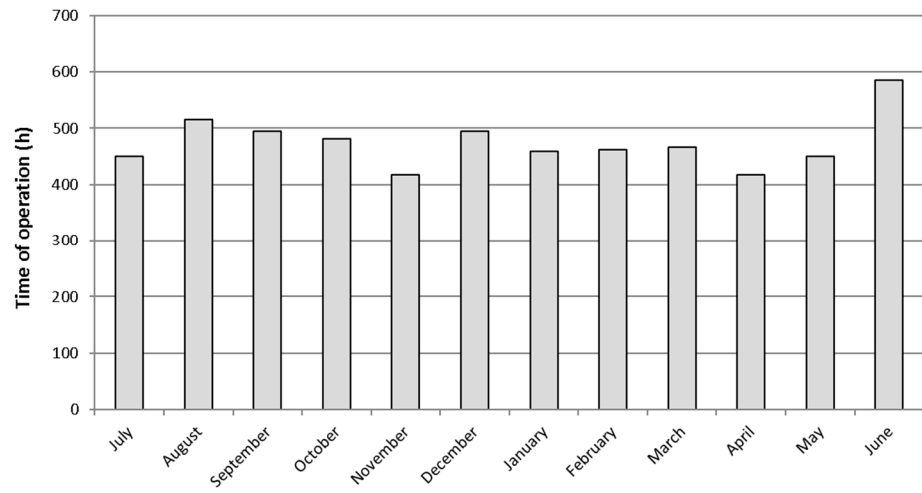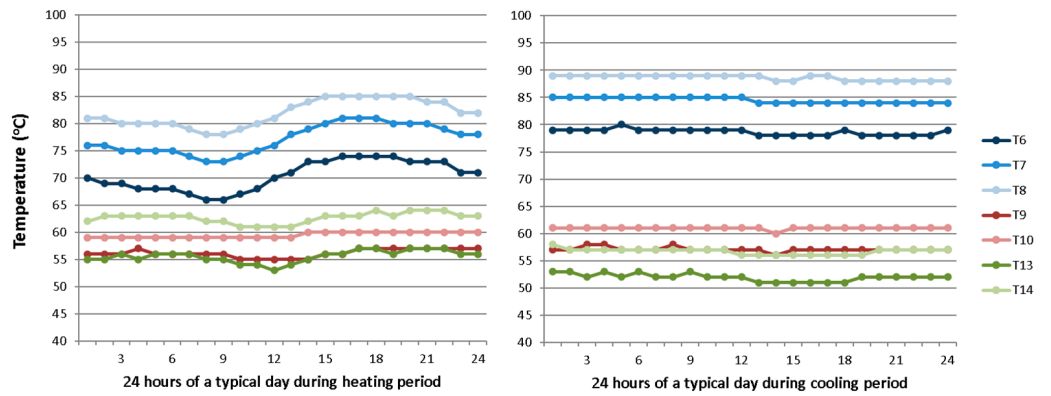
Figure 4. Monthly hours of CHP operation.

Figure 5. Hourly fluctuation of monitored temperatures for one typical day of the heating period and one of the cooling period.
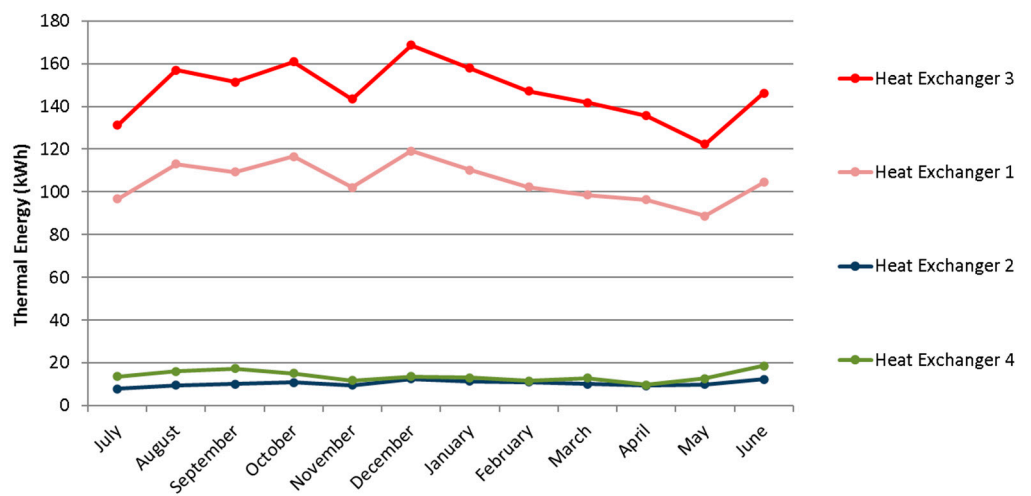

Figure 6. Monthly values of recovered thermal energy in each heat exchanger.
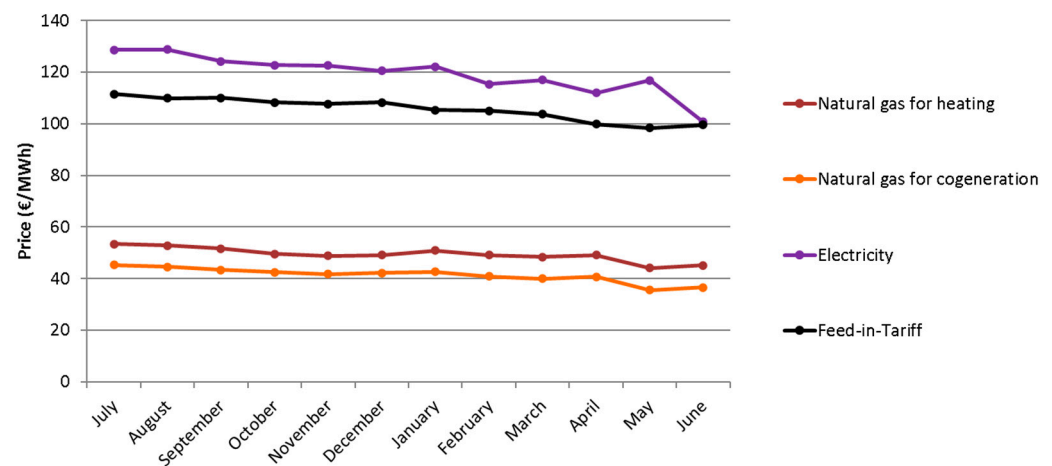
Figure 7. Monthly values of energy prices.

3.2. Energy Production

Figure 8 presents the monthly gas consumption of the CHP and the monthly energy balance. The recovered heat is used for space heating or space cooling, and for water heating. More specifically, the recovered heat from circuits 2 and 3 is used for water heating, while the recovered heat from circuit 1 is used for space heating during the heating period (15 October–April) and for space cooling during the cooling period (15 October–May), when the thermal energy from circuit 1 is transferred to the absorption chiller through the triode valve. Useful heat production is higher during winter months, while monthly energy production for water heating is quite stable, both following the load. Energy losses are estimated as the remaining energy from the fuel energy.

Figure 9 presents the monthly electricity production from CHP and the monthly avoided electricity consumption, corresponding to the energy used for space cooling when substituting the conventional electrical cooling system.

Figure 10 presents the recovered heat from CHP and Figure 11 presents the monthly avoided natural gas consumption. The recovered thermal energy is the total recovered heat *Q*, while the avoided natural gas consumption corresponds to the amount of substituted thermal energy from the conventional heating system. As expected, avoided thermal energy is higher during winter when heating energy needs and energy production from CHP are higher.

According to the percentage of energy needs coverage by CHP, as presented in Figure 12, the cogenerated heat covers about 50% of the hospital needs. However, during the cooling period, the load coverage is low, 25% on average.
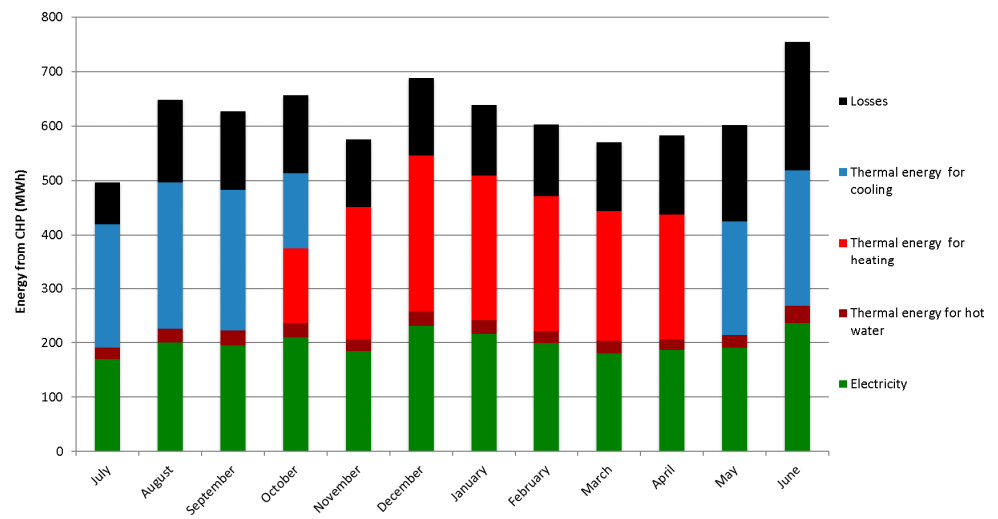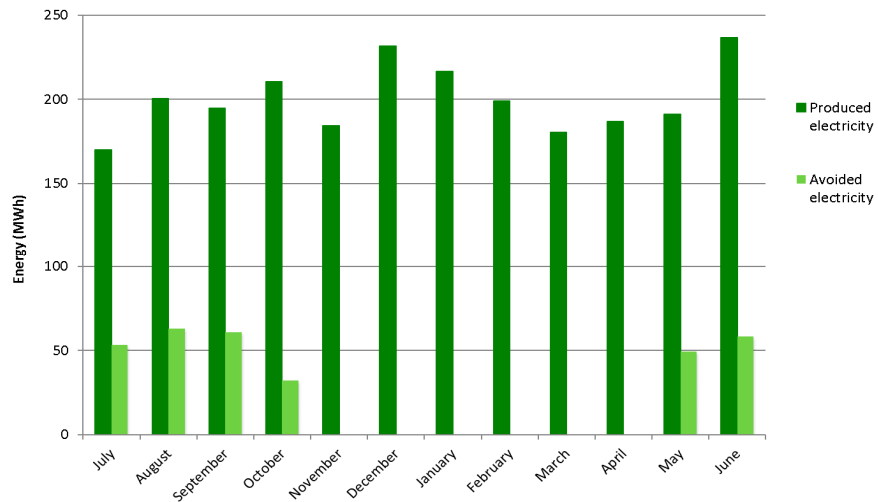
Figure 8. Monthly energy balance of CHP.

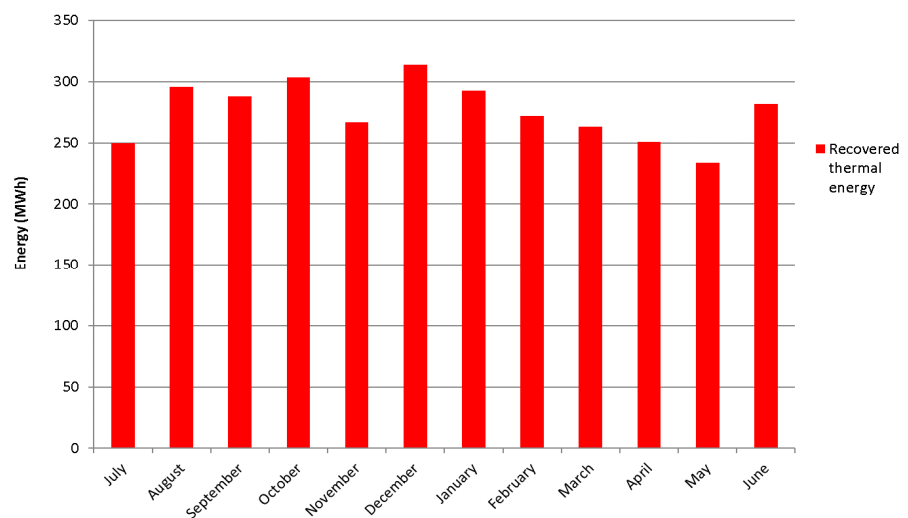**Figure 9.** Monthly electricity production from CHP and monthly avoided electricity consumption.

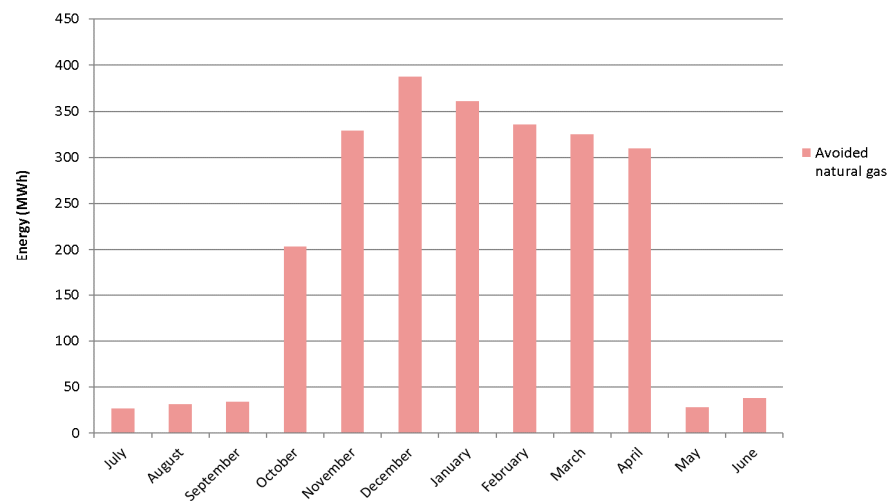**Figure 10.** Monthly recovered thermal energy from CHP.

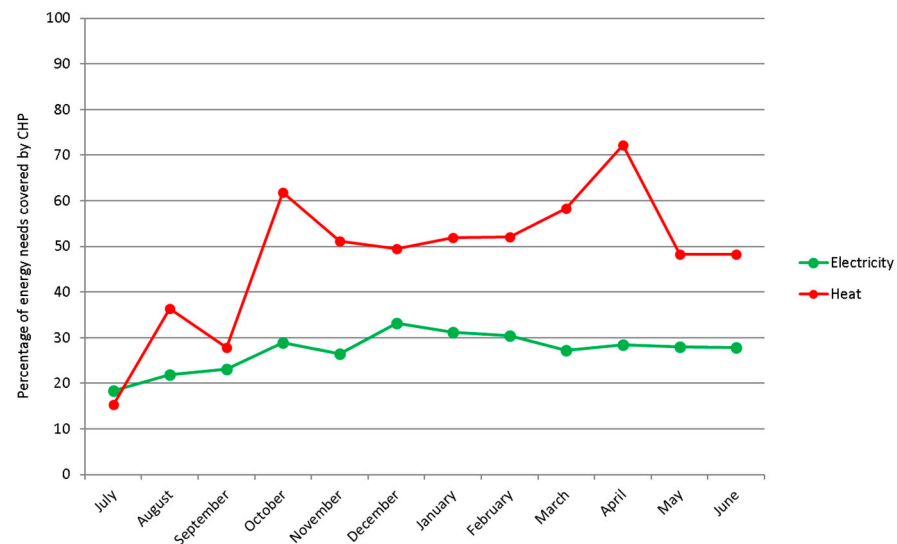**Figure 11.** Monthly avoided natural gas consumption.

Figure 12. Monthly electricity and thermal energy load covered by CHP.

3.3. Technical Performance

The evaluation of the technical performance is conducted by using two key performance indicators (KPIs): (a) the capacity factor (CF) and (b) the energy efficiencies (n_e and n_{th}).

3.3.1. Capacity Factor

The capacity factor (CF) is an indicator of the efficient use of the unit and the remaining operating potential. In Figure 13, the daily and monthly values of capacity factor versus time are presented. It is concluded that the sizing of the unit is correct, as daily values above 0.8 are often reached, especially during the heating season. However, the unit reaches only 55% average CF, indicating that the system is not used to its full potential. The values refer to the total time of the examined period, not just the time of operation. It has been observed from the analysis that although the operative power is generally high, it never reaches the nominal value. In addition to this, based on the operating schedule, the unit is employed only 65% of the time, as shown in diagram (b). The capacity factor is clearly strongly related to the total time of operation. Based on the thermal load coverage by the CHP, as presented in Figure 12, the unit could be employed more.
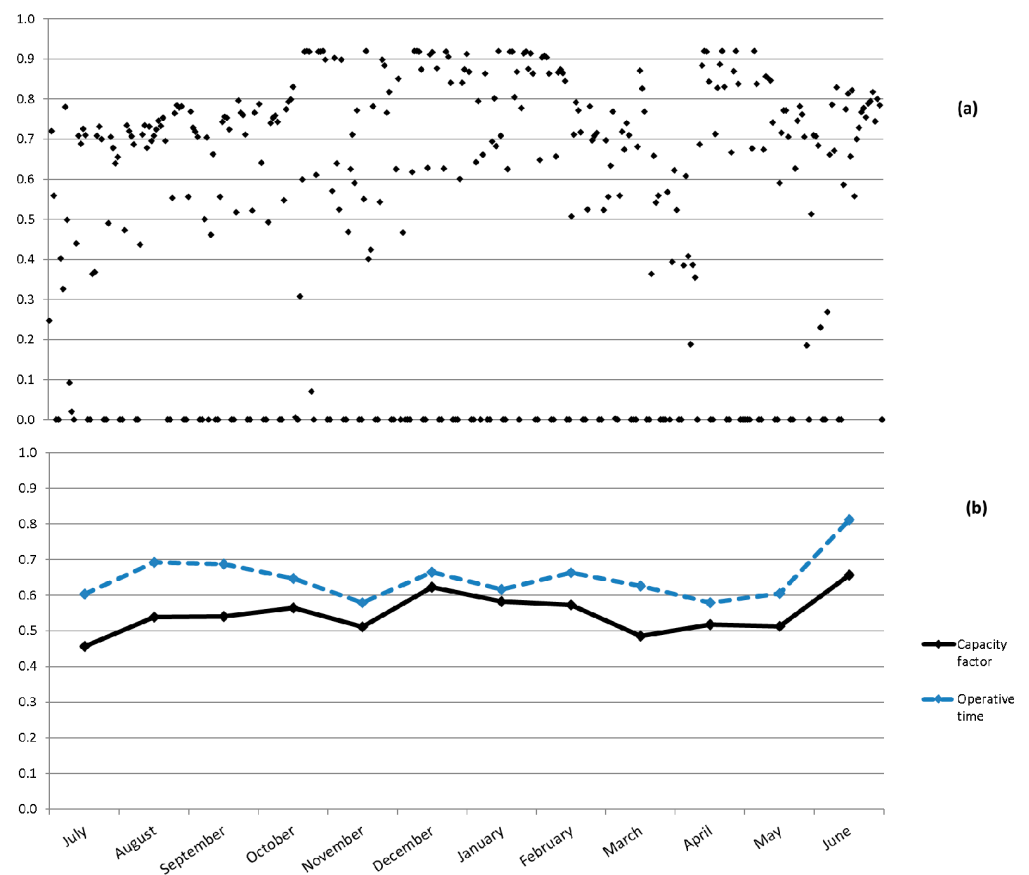
Figure 13. Capacity factor versus time. On the top diagram (**a**) are the daily values of *CF* versus time and on the bottom diagram (**b**) are the monthly values along with the operative time as a percentage of the total time.

3.3.2. Efficiency

Efficiency Based on Real Operation Data

Figures 14 and 15 present the real performance efficiency. In Figure 14, the daily values of electrical, thermal, and total efficiency versus time are presented. Electrical efficiency n_e is constantly above 30% and within the design values, fluctuating from 30 to 35%, while thermal efficiency n_{th} is steadier, around 46%, until May (2016) when it decreases, strongly related to the decrease of the flow rate in circuit 1, reducing the heat exchange margin in the exchanger and thus the thermal efficiency. Total efficiency is usually above the 75% threshold, characterizing the system as fully CHP operating, but also decreases in May, following the thermal efficiency curve and dropping slightly under 70%.

In Figure 15, hourly values of real performance efficiencies—electrical η_e, thermal η_{th} and total η_{chp}—are presented in diagram (**a**). Values show great fluctuation, especially during the beginning and end of the operating periods. The thermal efficiency is further analyzed in diagram (**b**) in terms of the thermal efficiency used for space heating, space cooling and water heating purposes, depending on how the recovered heat is used. It is apparent that the efficiency is reduced in the cooling mode due to the COP of the absorption chiller, which is 0.7. The thermal efficiency for water heating is steady throughout the year, and the values present less fluctuation.
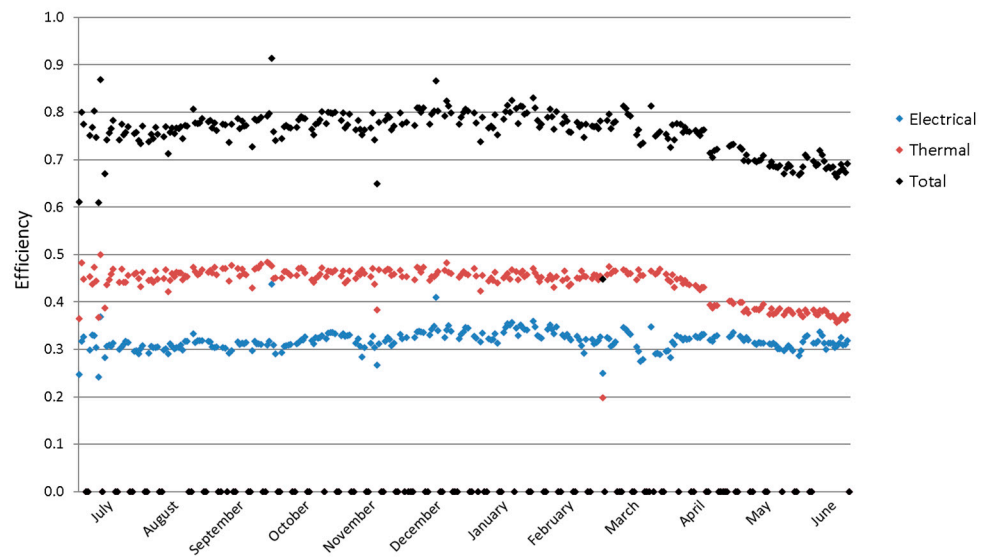
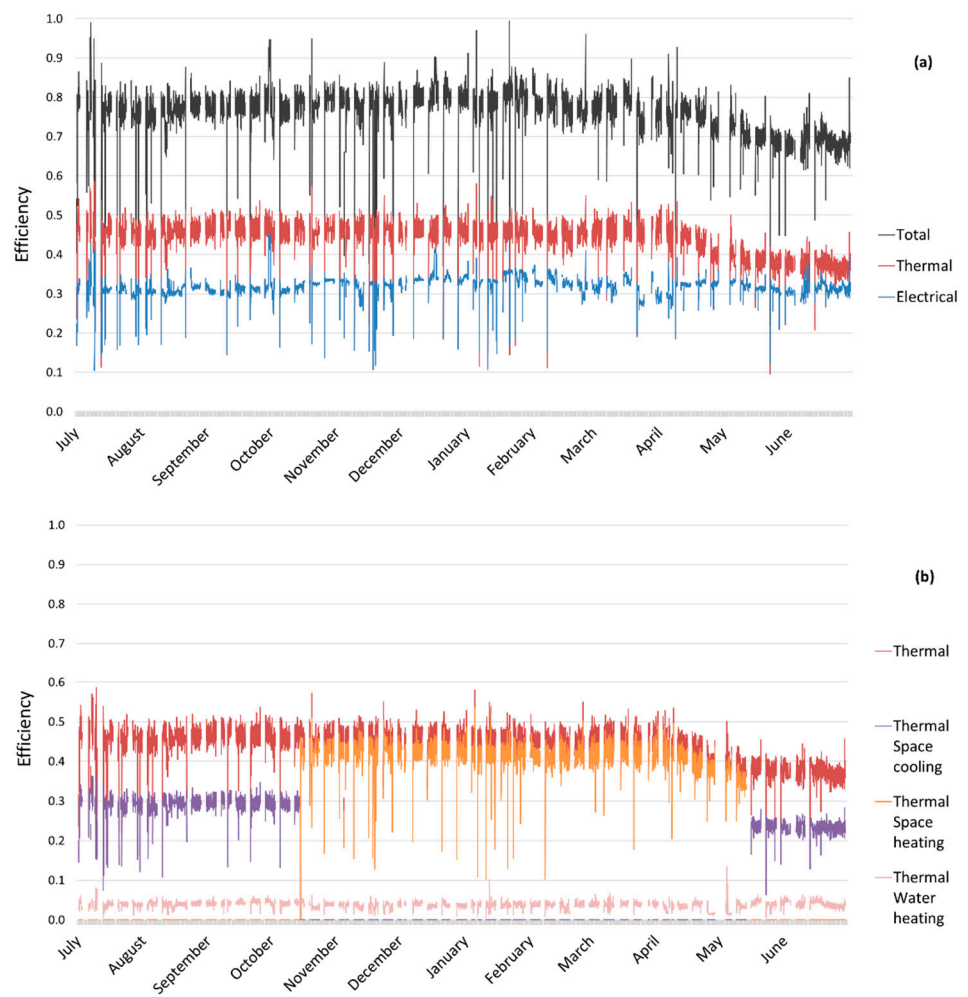**Figure 14.** Daily values of real performance efficiencies.

Figure 15. Hourly values of real performance efficiencies. On the top diagram (**a**) are the electrical η_e, thermal η_{th} and total η_{chp} efficiency and on the bottom diagram (**b**) are the thermal efficiency used for space heating, space cooling and water heating purposes, depending on how the recovered heat is used.

Efficiency at Partial Load. Comparison with Manufacturer Values

The hourly efficiency values versus the load are presented in Figure 16 and compared to the operating curve from the manufacturer's data, as presented in Table 1. Electrical efficiency is shown in diagram (a), thermal efficiency is in diagram (b), and it is further analyzed in terms of thermal efficiency from exhaust gas in diagram (c) and thermal efficiency from engine cooling in diagram (d), while the total efficiency is shown in diagram (e).

Electrical efficiency values are very close to the design efficiency curve, especially for loads close to nominal power. It is confirmed that with lower operating power, efficiency is also lower.

Thermal efficiency values are lower than the maximum values presented in the manufacturer's data, confirming that in real conditions, the system recovers less thermal energy and has greater energy losses. The curve is also different, presenting a proportional relationship between efficiency and power instead of inversely proportional. Thermal efficiency from exhaust gas is closer to the manufacturer's data. The exhaust gas is discharged at a 118 °C average temperature from heat exchanger 3 to heat exchanger 2 and at 59 °C from heat exchanger 2 to the environment, which is higher than the temperature from the manufacturer's data. The thermal efficiency from engine cooling is greatly reduced in lower loads. It is apparent that more thermal energy could be recovered from cooling the engine.

The total efficiency level is mostly reaching 70%. Based on the design characteristics, in partial loads, the electrical efficiency is decreased while the thermal efficiency is increased, thus keeping the overall efficiency quite steady. However, here, the efficiency is greatly reduced at a lower operating power due to thermal efficiency reduction.

Partial Load Model

Figure 17 presents the hourly consumption of the unit and the thermal load production versus power. Both parameters are presented together in one graph and compared to the manufacturer's data. The fitted linear equation is included. For operation at a certain power level, consumption is higher and thermal recovery is lower compared to the manufacturer's data, with the values, however, remaining close. As the CHP efficiencies depend on the consumed and produced energy, the relationship between those and the operative power is examined first. The derived equations of natural gas consumption G and recovered thermal energy Q from CHP versus power, for hourly operation, are:

$$G = 2.03P + 456 \tag{20}$$

$$Q = 0.92P + 191 \tag{21}$$

The derived equations modeling the operation and calculating the efficiencies based on operating power are:

$$n_e = \frac{E}{G} = \frac{P}{2.03P + 456} \tag{22}$$

$$n_{th} = \frac{Q}{G} = \frac{0.92P + 191}{2.03P + 456} \tag{23}$$

The resulting curves are presented in Figure 18 and compared to the manufacturer's data. The difference in the achieved efficiency increases as the operating power decreases, both for the electrical and the thermal efficiency, as also pointed out in Figure 16. For an operative power above 360 KW, the overall efficiency is higher than 75%, so the system is considered as fully CHP operating.
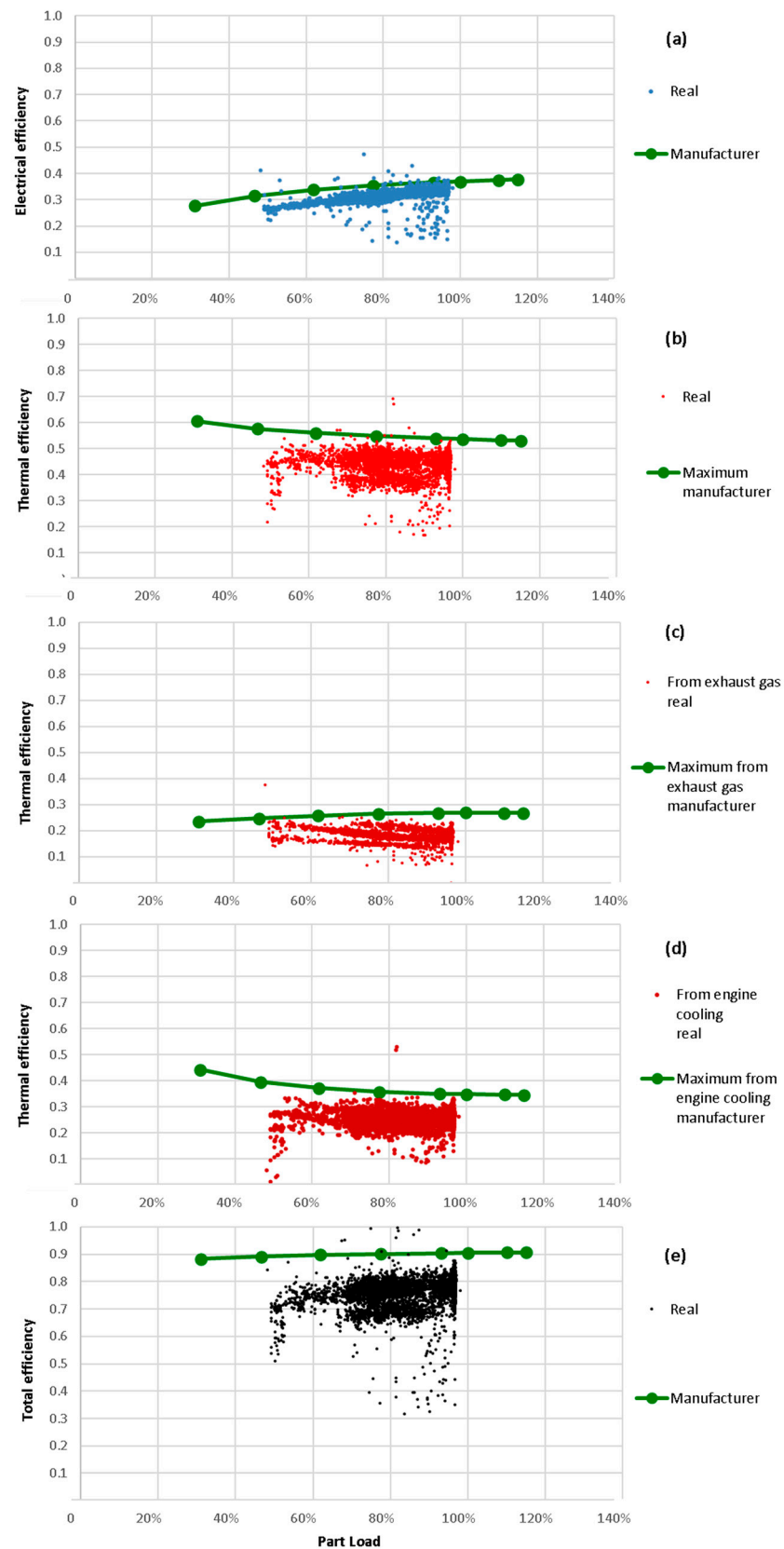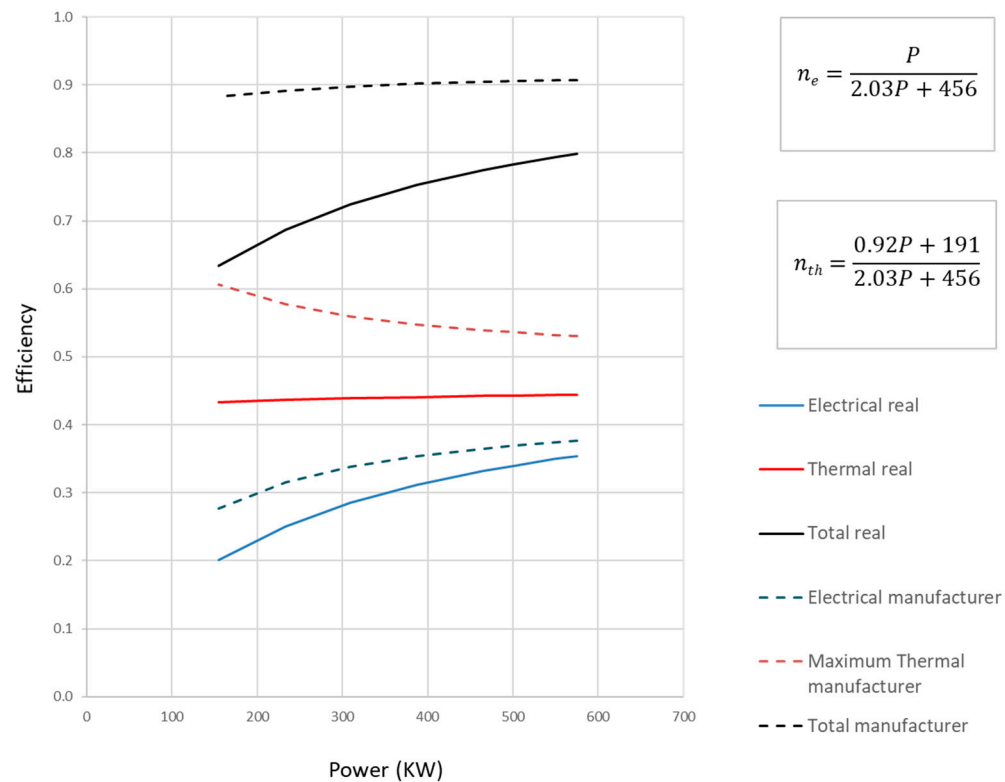
Figure 16. Electrical, thermal, and total efficiency hourly values versus power in part-load operation. Comparison with manufacturer's values. Diagram (**a**) shows the electrical efficiency, (**b**) the thermal efficiency, (**c**) the thermal efficiency from exhaust gas, (**d**) the thermal efficiency from engine cooling and (**e**) the total efficiency.
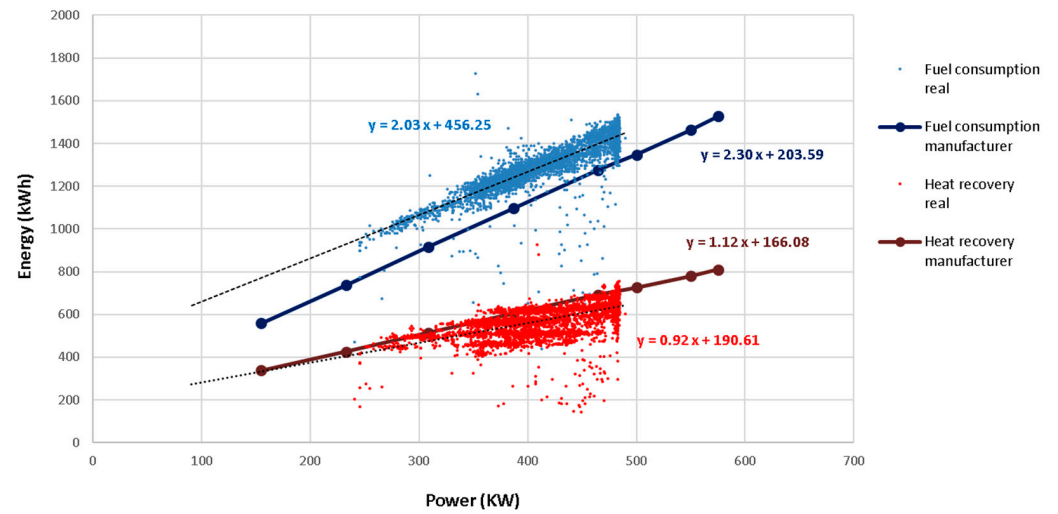
**Figure 17.** Hourly consumption and heat recovery versus power along with the fitted linear equations.

Figure 18. Electrical, thermal, and total efficiency curves versus operating power. Comparison with manufacturer's values.

3.4. Economic Performance

Economic performance is evaluated by using the cost of produced electricity as the key performance indicator.

The monthly cost of electricity produced from CHP, the $C_{e,chp}$, is presented in Figure 19, along with the cost of electricity purchased from the grid and the feed-in tariff price. The cost of produced electricity when the recovered heat is used for heating $C_{e,h}$ and the cost when it is used for cooling $C_{e,c}$ were also presented and analyzed separately. The achieved cost presents high fluctuation, depending on the use of the cooling function, with an average price of 75 €/MWh. The optimal operation is from November to April, during

heating mode. The use of the cooling function reduces the overall efficiency, and so, as expected, the cost is lower during winter months and higher during summer. Compared to the cost of electricity purchased from the grid, the CHP electricity cost is always lower. In addition to this, both prices $C_{e,h}$ and $C_{e,c}$ are lower than C_e. Therefore, the use of CCHP remains profitable in both functions. If the electricity were not used on site, it would be sold to the grid at the FiT price, as defined in Greek legislation. The use of CHP is still advantageous; however, the profit margin is gradually shrinking as the FiT has been decreasing.
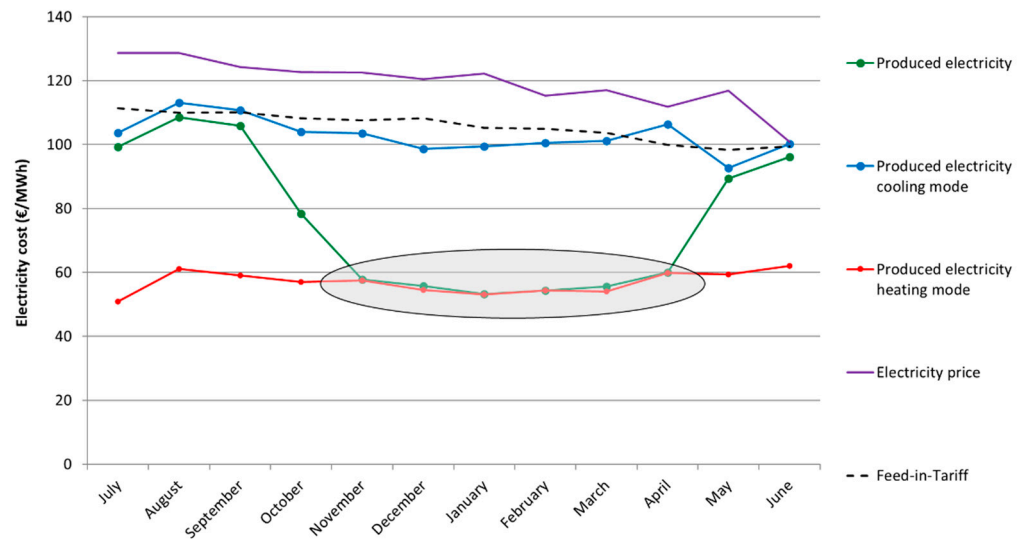
Figure 19. Monthly average cost of electricity produced from CHP, monthly average costs for heating mode and for cooling mode. Comparison with the price of electricity purchased from the grid and the FiT. Optimal operation is indicated in the highlighted shape.

4. Conclusions

The analysis and evaluation of energy efficiency and cost performance related to an installed CCHP system operating in a hospital have verified the system's technical characteristics and highlighted the success of the system in covering the energy needs of the hospital resulting in energy and cost savings.

Overall, the CHP system achieves satisfactory performance in terms of electricity production, showing efficiency results that are close to those presented by the manufacturer. This result is safe and accurate based on energy providers' data, in situ measurements, SCADA measurements, and energy balance equations. Electrical efficiency n_e is constantly above 30%, and within the design values.

Thermal energy is recovered through exhaust gas energy and through the cooling of the engine. The cogeneration unit achieves significant heat recovery as well; however, under real operating conditions it does not achieve the maximum heat recovery. Thermal efficiency n_{th} is around 45%. Total efficiency is usually above the 75% threshold characterizing the system as fully CHP operating.

Efficiency is strongly related to the operating power, and in lower power, efficiency is lower as well. The curves fluctuate more as the performance is influenced by many factors affecting the operation of the building and CHP system. Performance is verified in a wide range of operating conditions. However, the inefficiencies related to operating uncertainty are significant and proven to affect the performance, highlighting the need for continuous operation as much as possible.

Cooling is a way to utilize the thermal load when no thermal needs are present, thus extending the operating period of the unit; however, the overall performance of trigeneration is lower than that of cogeneration due to the COP of the absorption chiller, which is 0.7.

Sizing of the unit is crucial to ensure that the unit is used to its full potential. In addition to this, the operating schedule should be designed to increase the capacity factor.

The economic potential is verified in all the examined cases. The operation of the CCHP is cost effective in both the heating and cooling function, as the cost of electricity from cogeneration is lower than the cost of purchased electricity. The most profitable operation, however, is the heating mode. In the case of selling the electricity to the grid, the use of CHP is still advantageous if the FiT price is higher than the cost of electricity produced by CHP. The profit margin should determine whether the electricity is used or sold.

Overall, it can be concluded that the implementation of a CCHP system in a hospital, when designed properly, is a successful energy saving application, with verified performance standards in the long term.

List of Symbols

P_{nom}	The nominal power (KW)
P	The operative power (KW)
t	The time of operation (h)
t'	The total time of the examined period (h)
F	The water flow rate (t/h)
T	The temperature (°C)
C_p	The specific heat capacity of water (kWh/t)
Q_{gas}	The total energy in exhaust from gas (KW)
C_{pg}	The specific heat capacity of exhaust gas (kJ/kg) is the specific heat capacity of exhaust gas
T_g	The exhaust temperature after turbine (°C)
T_r	The final temperature of exhaust gas when rejected to the environment (°C)
G	The natural gas consumption by the CHP system (MWh)
E	The electricity production from CHP (MWh)
Q	The recovered thermal energy from CHP (MWh)
G_α	The avoided natural gas consumption for conventional heating energy (MWh)
E_α	The avoided electricity consumption (MWh)
n_e	The electrical efficiency of the CHP (-)
n_{th}	The thermal efficiency of the CHP (-)
$n_{th,g}$	The thermal efficiency from exhaust gas
$n_{th,w}$	The thermal efficiency from engine cooling
n_{chp}	The total efficiency of the CHP (-)
n_b	The thermal efficiency of conventional boiler (-)
COP_α	The coefficient of performance of the absorption chiller (-)
COP_e	The coefficient of performance of the conventional electrical chiller (-)
f	The part of the recovered heat that is used for space cooling (-)
C_g	The natural gas price for heating (€/MWh)

C_{gc}	The natural gas price for cogeneration (€/MWh)
C_e	The electricity price (€/MWh)
C_m	The cost of maintenance (€/MWh)
$C_{e,chp}$	The cost of electricity produced by the cogeneration system (€/MWh)
$C_{e,h}$	The cost of electricity produced by cogeneration when the produced heat is used for heating (€/MWh)
$C_{e,c}$	The cost of electricity produced by cogeneration when the produced heat is used for cooling (€/MWh)

Abbreviations

CF	Capacity factor
CHP	Combined heat and power
CCHP	Combined cooling heating and power
FiT	Feed-in tariff
KPI	Key performance indicator

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