Utilizing the Equivalent Thermal Efficiency (ETE), Energy Utilization Factor (EUF) and Exergy Efficiency to Evaluate the Annual Performance of an Engine Trigeneration System in a Tropical Climate

Denilson Boschiero do Espirito Santo
Mechanical Engineering Faculty - Energy Department
State University of Campinas - SP - Brazil - sisterm@sisterm.com.br

Electricity generation through fossil fuels are a major source of CO_2 production and global warming implications. Decentralized electricity production through cogeneration and trigeneration systems can save primary energy in buildings and industrial processes if they operate with high energy utilization factor (EUF). In this paper a thermal system integration simulation is performed using the software COGMCI. The analysis considers characteristics of the system and of the individual equipment, design parameters, off design dynamics, site energy demands profiles and climatic data, to evaluate the annual performance of an engine trigeneration system at a tropical region hospital. The ETE (equivalent thermal efficiency) criteria is defined and utilized to compare centralized thermal plants and local cooling and heating production with the proposed engine cog/trig system. EUF, PEC (primary energy consumption) and exergy efficiency are also used in the analysis. Results reveals that engine trigeneration systems can (i) rise the country installed capacity, (ii) rise the country average thermal efficiency (iii) export electricity to the grid at low renewables production hours and/or grid peak demand hours and (iv) contribute with the demand response strategy. Results can contribute in the implementation decision, in the optimization of the solution and in the development of energy policies.

Keywords: integrated thermal simulation, trigeneration, COGMCI software, iterative procedures, engine, absorption chiller.

1. INTRODUCTION

The efficient use of natural resources is an important contribution to reduce the environmental impact of human activities. In the electricity generation field, most of the world electricity production comes from fossil fuels thermal plants [01]. While renewable electricity (mainly solar and wind) production is rising its participation in the global scenario, some challenges associated with a high participation of intermittent electricity production in the electrical grid still needs to be solved. Several technologies are being proposed and utilized to contribute for a stabilized electric grid, including quick start thermal plants, batteries, thermal plants operating at part load, hydropower plants, etc.

Hydropower plants allows dammed water use for electricity production at low renewables production hours. Quick start thermal plants, usually engines and gas turbines are also used as a solution, but with low/medium thermal efficiency. Thermal plants able to quickly change their power supply can also support the instability of solar and wind electricity production.

Renewables electricity production can lead to excedent electricity that can be used for hydrogen production and/or pump water to hydropower dams. Hydrogen and dammed water can be later converted to electricity at low renewables production hours and/or peak grid demand hours.

As renewables make greater contributions to our energy mix, balancing the grid is more challenging than ever. Every country should plan and explore their possibilities looking to improve the renewables electricity production while maintaining the grid stability. Better choices are a compromise between available options, natural resources, efficiency, emissions, country experience, strategic planning, etc.

Fossil fuel thermal plants is expected to continue participating as an important player in the electricity production market in the next years [02]. The challenge is to rise the countries average thermal efficiency and use lower CO_2 emission fuels. Natural gas cogeneration and trigeneration (cog/trig) systems can contribute is this migration process, producing electricity, heating and cooling at high efficiency. Cog/trig systems usually are designed to attend variable electrical and thermal loads, high efficiency needs to be evaluated at an annual basis [03].

The challenge associated with a such complicated analysis are directing to the design of electricity base loads cog/trig systems (prime mover operates at full load and produced power is all the time used in the site while excedent electricity is bought from the grid), reducing the project uncertainties and investment risks. Gvozdenac et al [04] discussed that real power plants operates with variable loads and this affects the calculation accuracy.

Base load cog/trig systems leave the demand response problem to the grid manager and sometimes is not the best solution for a given energy demand scenario. Oversized systems are able to export electricity (mainly outside building/process peak electricity demand). Siler-Evans et al [05] proposed strategies to incentive the adoption of cog/trig systems, they also proposed the use of larger engine operating in a microgrid.

Cog/Trig systems are not designed to meet all the site loads, Rim et al [06] evaluated the performance of a CCHP system with an absorption chiller and an electric chiller (hybrid chiller), both chillers are used to attend the cooling load. Optimization methods are being used to evaluate and integrate cogeneration with renewables [07].

District heating and cooling systems utilizing prime mover residual energy is also being proposed and evaluated. Kabalina et al [08] evaluated a gasifier gas turbine poligeneration system and Piacentino et al [09] evaluated diesel engine cogeneration for Italian small islands.

Cog/Trig systems size is affected by the local climate and energy loads. Fong and Lee [10] evaluated trigeneration systems in four different cities. They used the TRNSYS software to predict the heating and cooling loads.

Jana et al [11] discussed some poligeneration studies and possible configurations, seeing the technology as a future sustainable energy solution. Cog/trig systems can also be fuelled by biofuels [12].

Although most of the systems are evaluated using first law of thermodynamics efficiency indicators and simple monetary cash flow, the second law of thermodynamics, thermoeconomic [13] and thermoecological [14] analysis is being performed by researchers, revealing interesting aspects of cog/trig systems.

In this paper the equivalent thermal efficiency (ETE) criteria is defined and used to quantify the performance of an engine cog/trig configuration with different engines sizes and operational modes. The software [15] (COGMCI) is used to evaluate the engine cog/trig system annual performance, producing electricity, hot water and chilled water (cooling load). The software does the evaluation of the performance of the system considering hourly daily profile of energy demands and climatic data. Energy demands of a Brazilian university hospital situated at a tropical region were utilized as a case study. Climatic profiles of the hospital region were also utilized.

Energy utilization factor (EUF), primary energy consumption (PEC) and exergy efficiency are also used to compare the different proposed solutions.

2. CASE STUDY: HOSPITAL

To develop the analysis, loads of a local university hospital is assessed. The energy demand profiles were obtained through a data acquisition system (figure 1) installed to register the Clinic Hospital of the State University of Campinas energy demands. The data acquisition system was installed to monitor the total hospital electricity demand, sanitary use hot water demand, steam demand and the electrical demand of the electrical chillers at a one-hour time interval. These same loads were previously utilized in another paper [16] with a different engine cog/trig configuration. The steam demand will not be utilized in this study, since the hospital decided to eliminate the steam generator and the steam use equipment (laundry, kitchen, etc). The data acquisition system software displays the data in a computer and store them in files.

The hospital buy electricity from the electrical grid, produces hot water at combustible oil boilers and chilled water (air conditioning) at two water cooled screw compressor chillers.

Figures 2 and 3 reveals the annual (365 curves – blue lines) hospital electricity demand. Figures 4 and 5 reveals the hospital annual electrical chillers cooling load (air conditioning) – individual air conditioners are not included. Figures 6 and 7 reveals the hospital annual sanitary use hot water demand. Sanitary use hot water consumption occurs at bathroom (patient personal care), lavatories, kitchen, etc. Figure 8 reveals the annual local dry bulb temperature profile and figure 9 reveals the annual relative humidity profile, both were obtained by a climatic monitoring station located at the university campus.

Average daily energy demands profiles were grouped at eight different groups that were assumed to have similar behavior: i) summer weekdays (60 days), ii) summer weekends/holidays (29 days), iii) autumn weekdays (65 days), iv) autumn weekends/holidays (28 days), v) winter weekdays (67 days), vi) winter weekends/holidays (27 days), vii) spring weekdays (60 days) and viii) spring weekends/holidays

(29 days). Climatic data (dry bulb temperature and relative humidity) were grouped in four mean daily profiles, one for each weather station.

In figures 2 to 6 the eight average curves for each energy demand (electricity, chilled water and hot water) at each weather season at weekdays and weekends are revealed. At figures 8 and 9 four curves reveals the average dry bulb temperature and relative humidity at the different weather seasons.

Pernigoto et al [17] commented that "Simulations with typical years (or representative days) instead of multi-year weather data lead to less information but they are less time-consuming and results are easier to manage. They are also preferred to mitigate the effects of missing or wrong data in the collected series".

Electricity demand is higher at summer and between hours 6 to 20 mainly due to a higher hospital activity and air conditioning use (higher outside temperatures, solar incidence, etc) – see figures 4 and 5. Hot water consumption is higher in winter and peak consumption occurs (i) close to hour 8 mainly due to patients personal care, (ii) at hour 14 mainly due to kitchen use and (iii) between hours 18-22 due to kitchen and personal care use.

Table 1 shows the hospital hot water consumption and electricity consumption. The electrical chiller consumption is included in the electricity consumption (line 3), since the data acquisition system measures the hospital total electricity input. Sanitary use hot water flow revealed at line 1 of table 1 (figures 6 and 7) is converted to energy (line 2 of table 1) assuming that the water is warmed from 22.2ºC (make-up temperature) to 50ºC (hospital sanitary use water demand temperature).

At table 2 the average daily consumption is multiplied by the number of days in each group. At the last column of table 2 the groups energy consumption is summed, revealing the annual hospital building energy consumption.

More complex data acquisition systems that evaluate the efficiency of the existing equipment (boiler, steam generator and electrical chillers) can be implemented to allow for a better analysis of the site energy consumption.

TABLE 1 – DAILY ENERGY CONSUMPTION

	Daily Analysis	summer wdays	summer wends	autumn wdays	autumn wends	winter wdays	winter wends	spring wdays	spring wends
1	hot water demand (m3/h/day)	36.35	27.97	55.46	33.68	62.67	38.51	45.92	26.13
2	hot water demand (kWh/day)	1,171.85	901.71	1,788.27	1,085.80	2,020.54	1,241.73	1,480.48	842.30
3	electricity (kWh/day)	35,970.10	29,544.41	30,129.83	24,318.64	27,519.14	22,779.24	31,683.06	26,110.54

TABLE 2 – ANNUAL ENERGY CONSUMPTION

	Group Analysis Energy	summer wdays	summer wends	autumn wdays	autumn wends	winter wdays	winter wends	spring wdays	spring wends	annual consumption
1	hot water demand SC (kWh/year)	70,310.88	26,149.53	116,237.29	30,402.51	135,376.05	33,526.63	88,828.50	24,426.61	525,258.00
2	electricity (kWh/year)	2,158,206.00	856,788.01	1,958,439.08	680,921.95	1,843,782.05	615,039.48	1,900,983.42	757,205.52	10,771,365.49

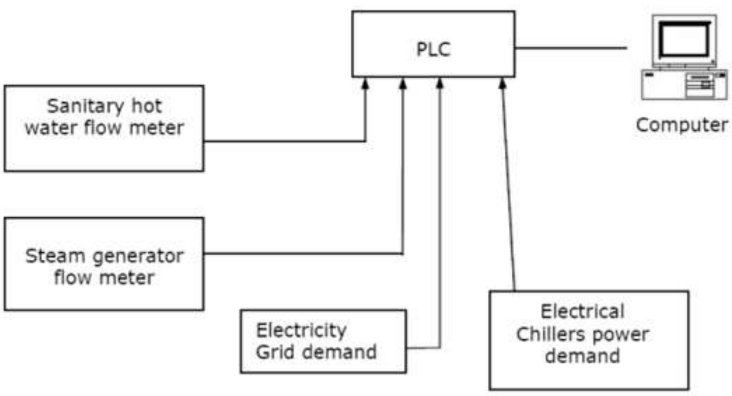

Figure 1 – data acquisition scheme

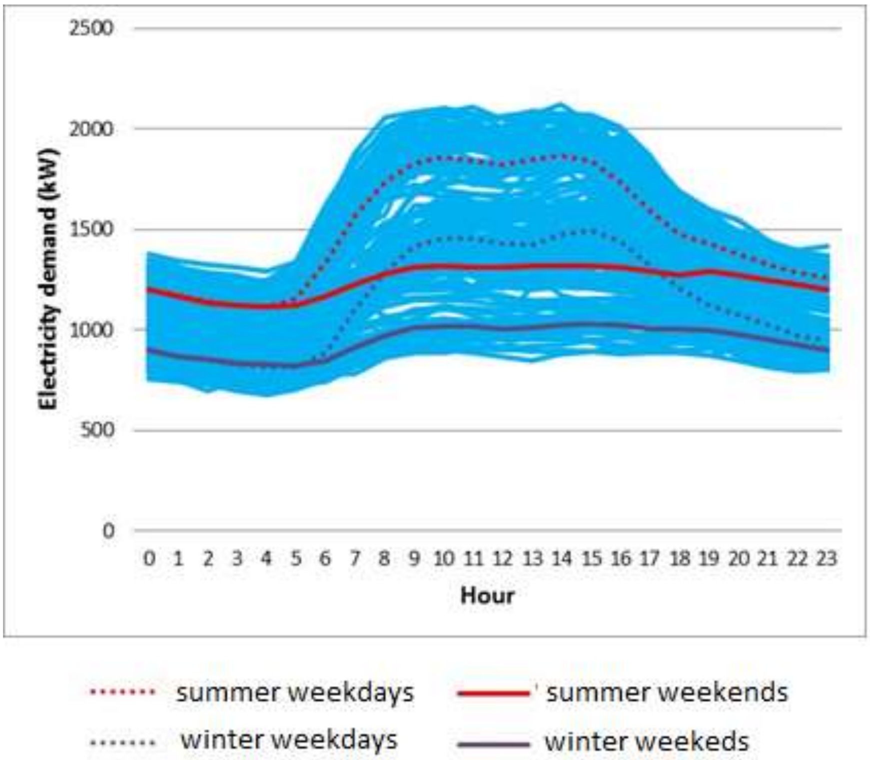

Figure 2 – Hospital electricity demand (kW) – summer and winter

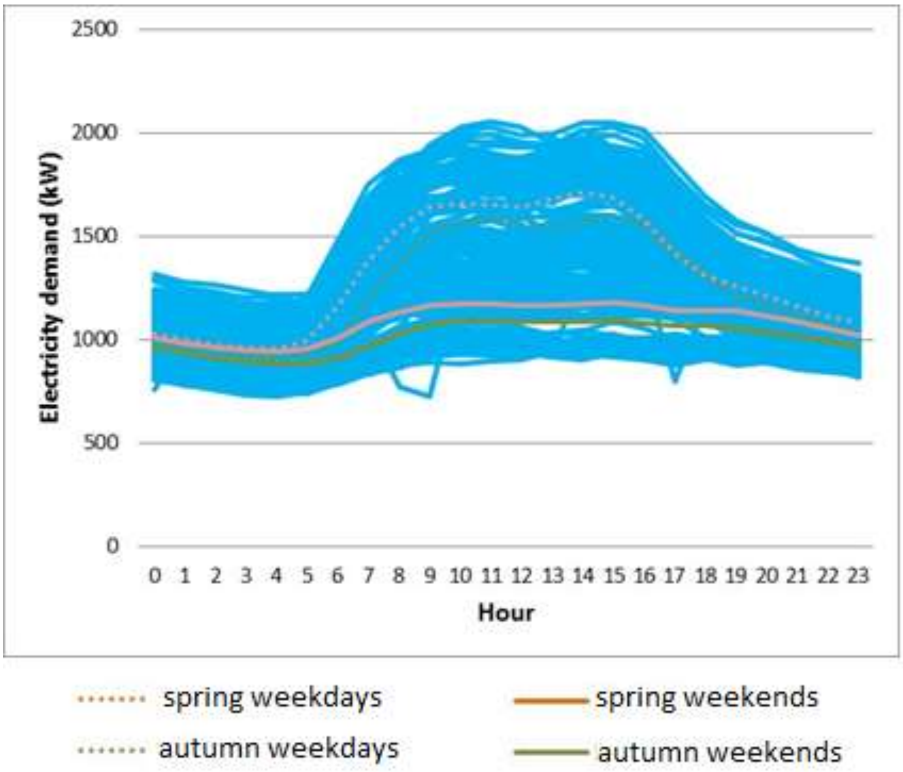

Figure 3 – Hospital electricity demand (kW) - autumn and spring

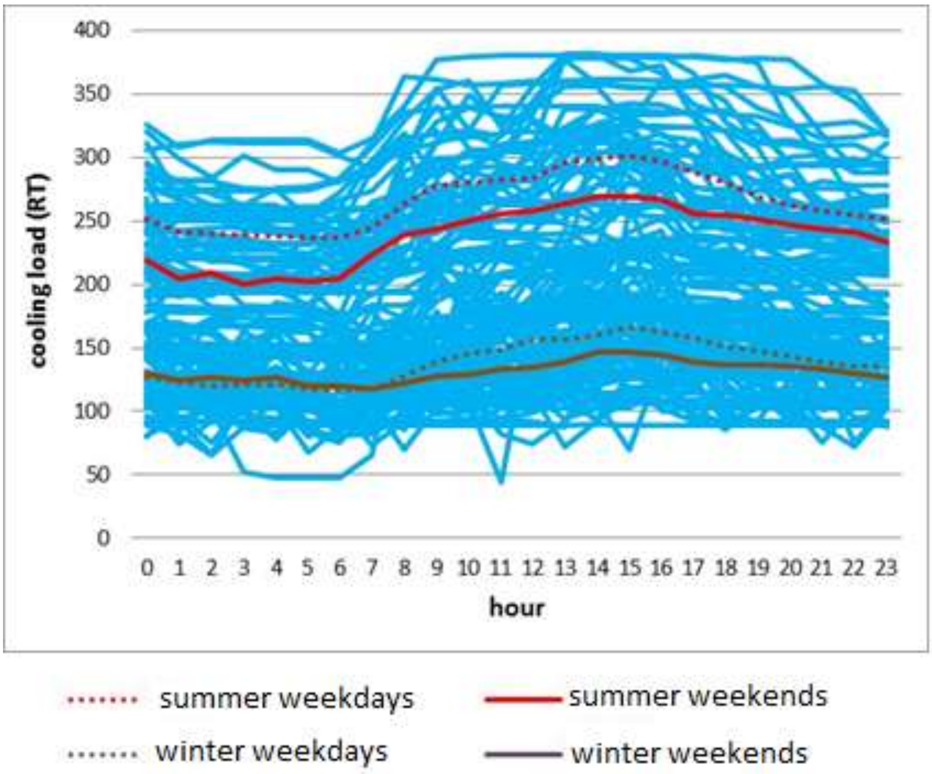

Figure 4 – Hospital cooling load (refrigeration tons) – summer and winter

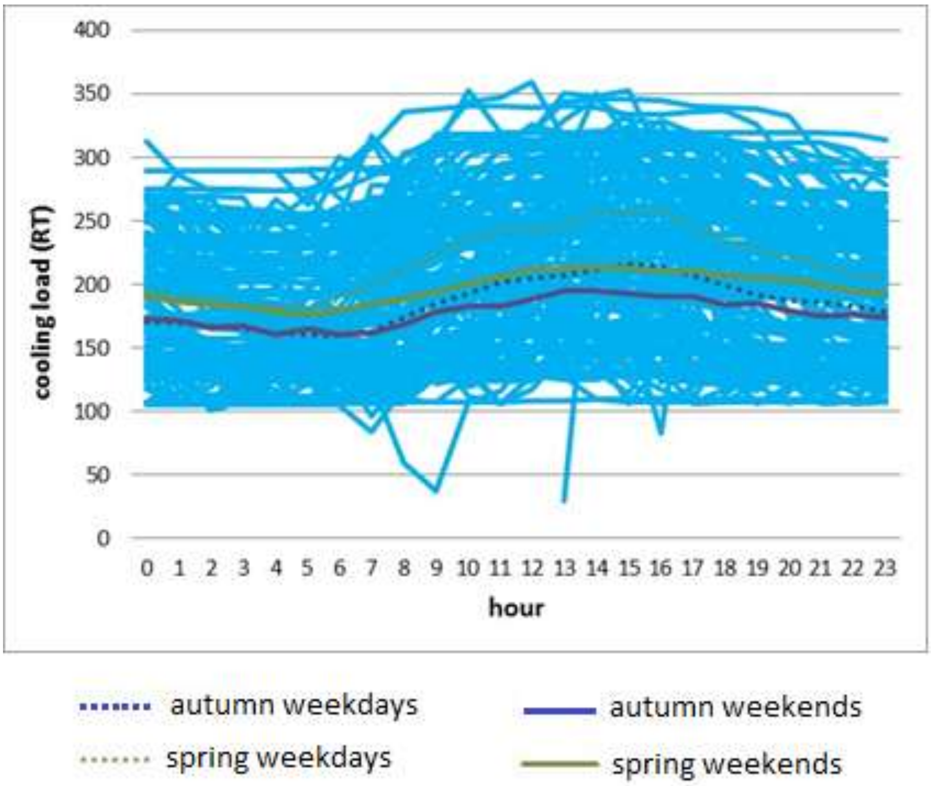

Figure 5 – Hospital cooling load (refrigeration tons) - autumn and spring

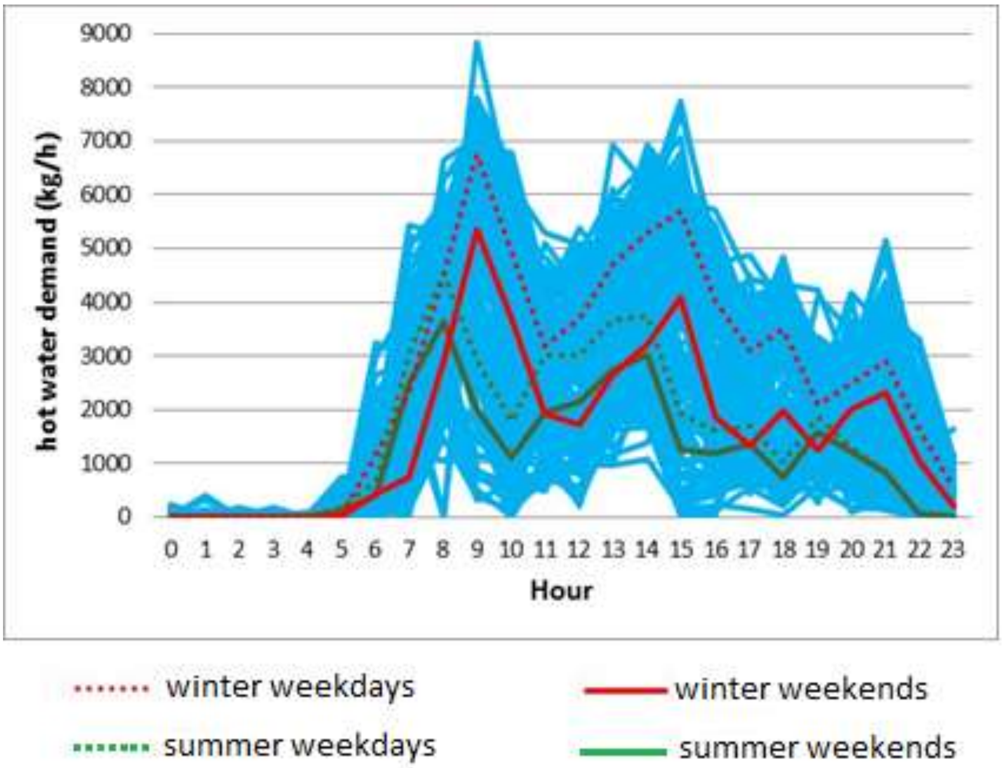

Figure 6 – Hospital sanitary use hot water demand (kW)- summer and winter

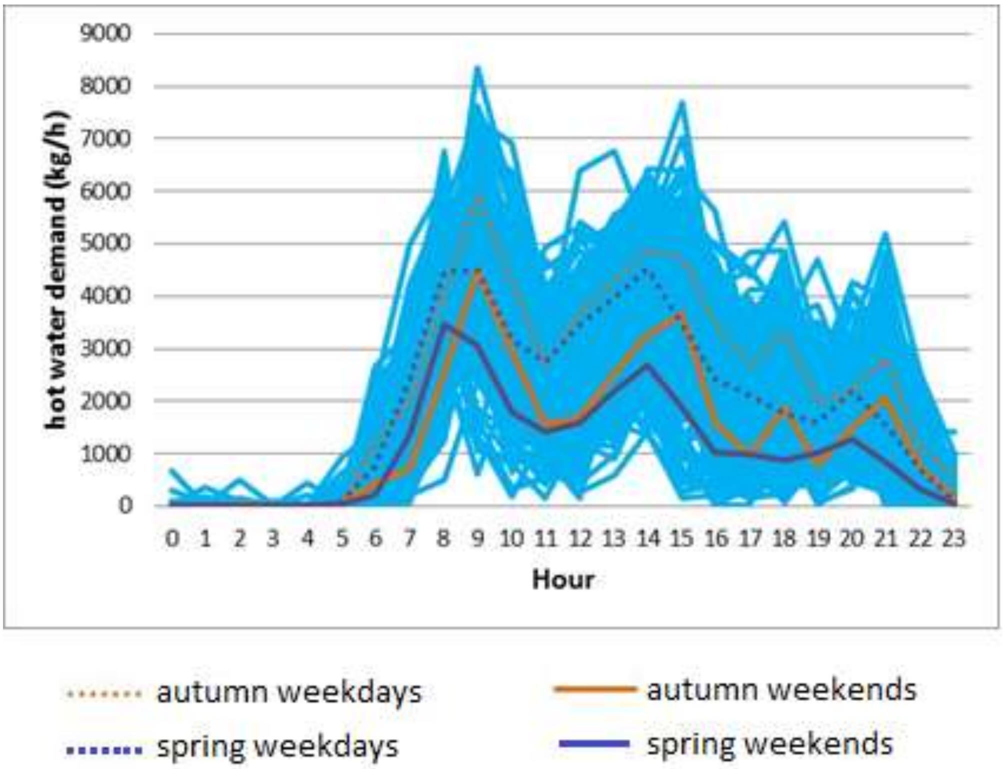

Figure 7 – Hospital sanitary use hot water demand (kW) - autumn and spring

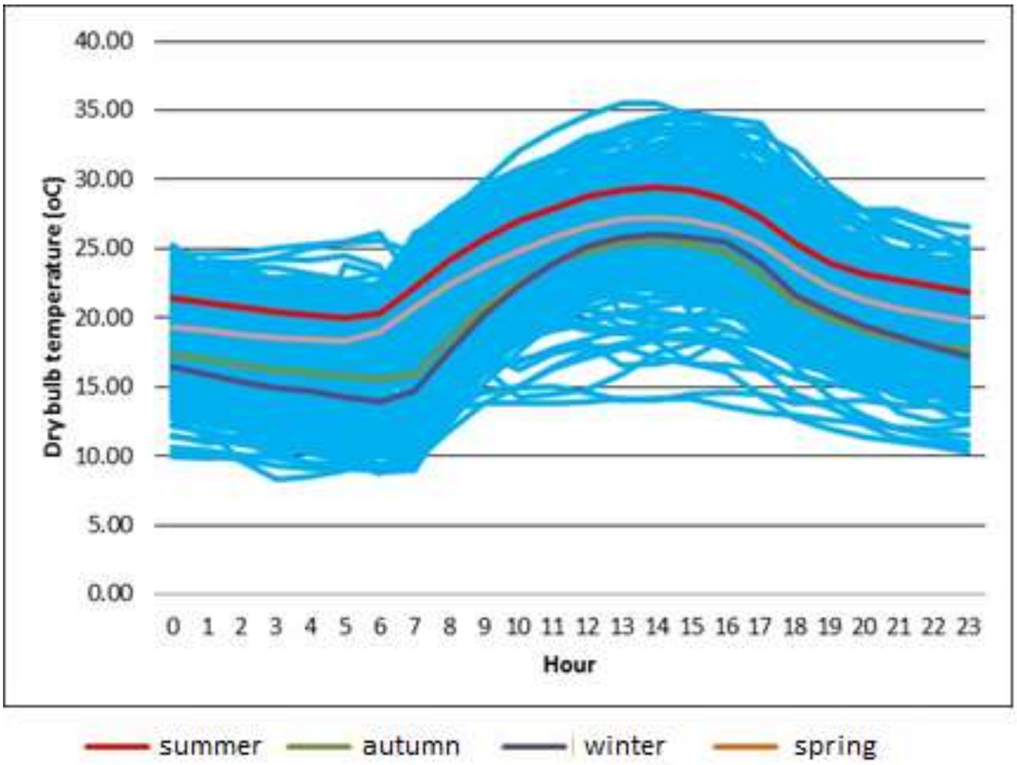

Figure 8 – site climatic data - dry bulb temperature

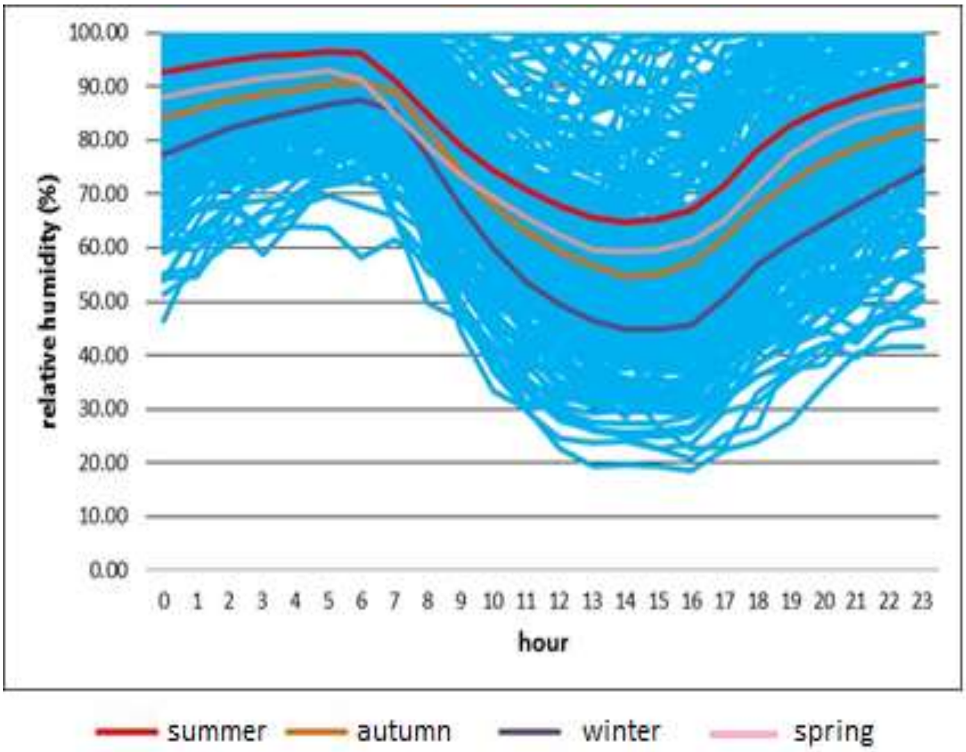

Figure 9 – site climatic data - relative humidity

3. METHODOLOGY

The analysis and results developed in this study were obtained by mean of the software COGMCI consisting of Fortran engineering programs and a Delphi interface – a demo version of the software can be asked to the author. Graphical results are generated by a spreadsheet (Excel) that imports data from result files. The Fortran programs is composed of four main algorithm and more than 30 subroutines dealing with (i) different engines, (ii) water and steam properties, (iii) exhaust gas properties, (iv) hot water absorption chiller selection and simulation, (v) exhaust gas and hot water absorption chiller, (vi) heat recovery steam generator (HRSG) design and simulation, (vii) HRSG economizer design and simulation, (viii) exhaust gas heat exchanger (EGHE) design and simulation, (ix) cooling tower design and simulation, (x) air cooler design and simulation, among others.

The main program controls data input, output and all calculations. Calculation procedures use polynomial curve fitting (engine and absorption chiller performance); deterministic modeling or mathematical representations of physical phenomena (heat transfer and pressure drops); and physical properties (water and exhaust gases). Four computational algorithm involving several iterative procedures was developed, simulating the system as an integrated thermal system, i.e., considering all pieces of equipment as operating as a single system. It produces results as a function of demands, energy supplied by engine, design parameters, equipment performance, and simplified assumptions. The hourly profile analysis simulation approximates the dynamic nature of energy consumption in buildings and the dynamics of thermal equipment performance in an integrated system by a series of quasi-steady-state operating conditions with one-hour time-step [18].

The COGMCI software is being developed for close to 20 years. It was previously utilized to develop others case studies [16, 19-21].

4. COGENERATION CONFIGURATION

Figure 10 shows the trigeneration configuration evaluated here. This scheme is being proposed since it produces the three different hospital energy consumption products (electricity, chilled water and hot water). Flows are identified in the text by brackets. The cogeneration system is formed by one internal combustion engine, engine primary circuit (PC) and engine secondary circuit (SC) hot water, one exhaust gas heat exchanger (EGHE), one hot water single stage absorption chiller (AC), and auxiliary equipment (pumps, cooling towers, air coolers, heat exchangers, etc). The SC recovers energy from the engine intercooler and uses it to warm water for sanitary purposes at HE2. The PC recovers energy from the engine jacket, the water is reheated utilizing the energy of the engine exhaust gas at the EGHE. After the reheat it is directed to the absorption chiller for chilled water production. If there is energy excess in the primary circuit it can be used to warm water for sanitary purposes at HE1 (after recovery at HE2). Table 3 reveals the thermodynamics state properties of figure 10.

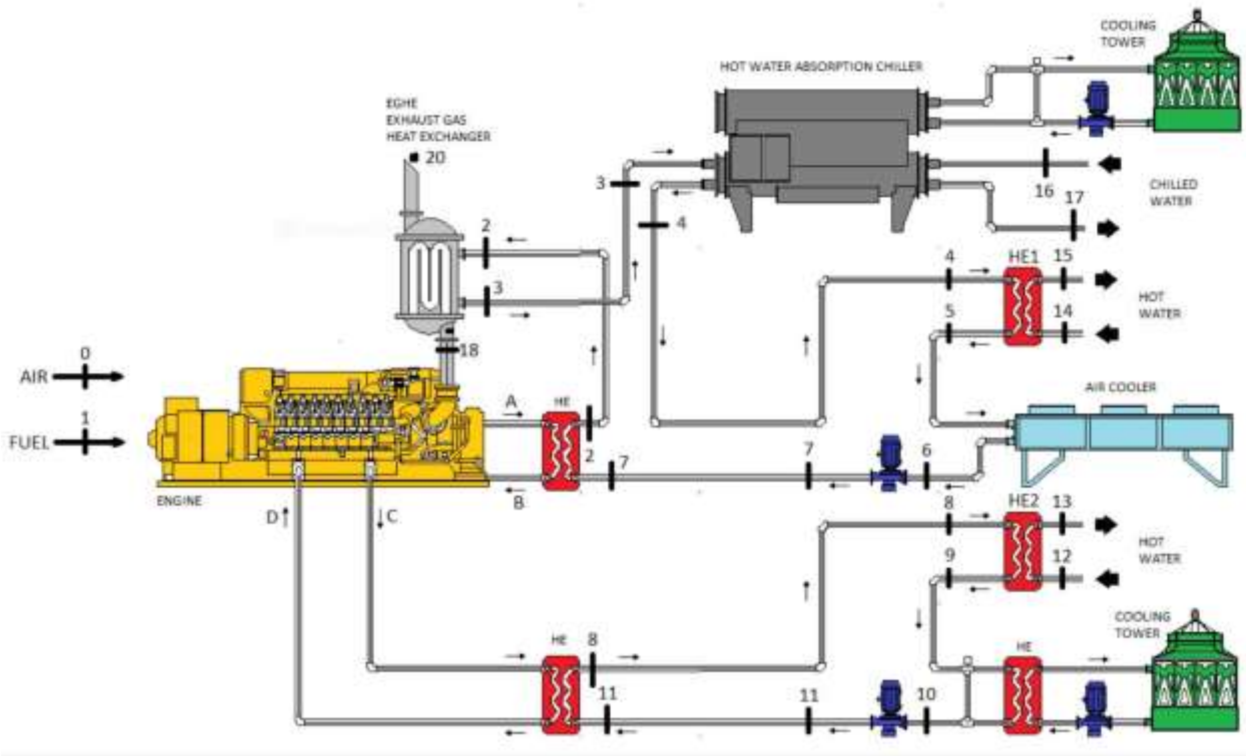

Figure 10 – trigeneration scheme

Table 3 – thermodynamics properties – figure 10

flow number	pressure (kPa)	temperature (oC)	mass flow (kg/s)	enthalpy (kJ/kg)	entropy (kJ/kg.K)
0	100.000	25.000	1.753	298.800	5.699
1	100.000	25.000	0.061	45,462.000	0.000
2	462.500	93.000	11.188	389.867	1.227
3	375.000	106.661	11.188	447.381	1.381
4	287.500	81.081	11.188	339.647	1.088
5	200.000	80.000	11.188	335.042	1.075
6	200.000	80.000	11.188	335.042	1.075
7	550.000	80.000	11.188	335.324	1.075
8	275.000	43.000	9.264	180.229	0.612
9	150.000	40.000	9.264	167.582	0.572
10	150.000	40.000	9.264	167.582	0.572
11	400.000	40.000	9.264	167.806	0.572
12	300.000	22.222	1.437	93.437	0.328
13	250.000	41.560	1.437	174.189	0.593
14	250.000	41.560	1.437	174.189	0.593
15	200.000	50.000	1.437	209.421	0.703
16	400.000	13.333	37.600	56.352	0.200
17	300.000	7.222	37.600	30.640	0.110
18	102.000	414.000	1.814	773.893	7.911
19	102.000	414.000	1.814	773.893	7.911
20	100.000	109.667	1.814	416.575	7.227

Table 4 – engine performance data

	Engine 1	Engine 2	Engine 3	Engine 4	Engine 5
Model	CG170-12	CG132-16	CG132-12	CG132-8	CG170-16
Engine power (kW)	1200	800	600	400	1560
Primary circuit energy (kW)	612	385	297.26	188.17	804
secondary circuit energy (kW)	116	58	51.05	27.02	144
exhaust gas energy (kW)	757	620	453	317	1013
exhaus gas flow (kg/h)	6531	4434	3349.6	2234.4	8589
exhaust gas temperature (oC)	414	488	475	493.9	420
PC water entering/leaving (oC)	80/93	84/92	77.8/87.8	83.9/92.2	80/93
SC water entering/leaving (oC)	40/43	40/46	40/45	40/43.9	40/44
electrical efficiency (%)	43.4	41.6	41.4	41.4	43

Table 4 reveals some full load engine operating data, engine 1 (Caterpillar CG170-12) [22] is utilized at the detailed case study, while the other engines will be utilized to evaluate other engine possibilities and operational modes (see section 7).

Caterpillar engine CG170-12 – engine 1, has an electric power of 1200 kWe and 43.4% electrical efficiency at full load operating with natural gas. Energy in the primary circuit (jacket water), secondary circuit (intercooler) and in the exhaust gas are revealed at table 4. Design temperatures of hot water at the primary and secondary circuits are defined by the manufacturer as constraints to allow the engine to achieve the specified performance, overhaul schedules and avoid operating failures. The engine part load performance curves (not revealed at this study) were introduced in the software and utilized in the simulation. Espirito Santo [16] revealed a real engine energy balance, exhaust gas flow and temperature curves at part load. Correction for atmospheric pressure assumes a 0.7% loss of power for each 100 meters above 500 meters. Correction for dry bulb temperature assumes a 0.5% loss of power for each degree Celsius above 25°C.

At design condition, secondary circuit hot water enters the engine [flow 11] at 40°C (fixed) and leaves it [flow 8] at 43°C, while primary circuit hot water enters the engine [flow 7] at 80ºC and leaves it [flow 2] at 93ºC. Water flows at primary and secondary circuits are designed taking into account the energy at the circuit and the design temperature difference (constant flow).

The EGHE is simulated according to the methodology proposed by Ref. [23]. A heat loss of 1% was assumed. Exhaust gas composition is assumed to be constant, and properties are evaluated at its mean temperature at the EGHE. The exhaust gases temperature leaving the EGHE [flow 20] is designed to be 16.7ºC higher than the primary circuit hot water temperature entering the EGHE [flow 2] - (approach point). Primary circuit water temperature leaving EGHE [flow 3] is calculated as 106.6ºC.

The absorption chiller (AC) selection and simulation is based on performance curves from a manufacturer (Trane Company, 1989) [24]. The selected absorption chiller has a nominal capacity of 520 tons (1774 kW) based on saturated steam at 184 kPa as the heat source, chiller water being produced at 7.2°C [flow 17] with 5.5°C temperature difference [flow 16] and water entering the condenser at 29.4°C. The software selects the AC based on the primary circuit water flow and temperature difference while the chilled water temperature [flow 17] and the water temperature entering the condenser should also be defined. PC hot water enters the AC generator at 106.6ºC [flow 3] and leaves it at 81.08ºC [flow 4], chilled and condensed water temperatures are as defined at the nominal capacity condition (these represents the design condition of the chilled water plant at the hospital). The water flow at the condenser and absorber is as required by the AC manufacturer. The AC is assumed to avoids electricity demand at the electrical chillers by a rate of 0.78 kW/RT (COP=4.5). Rim et al [06] used a COP equal to 4 for the electrical chillers.

The simulated AC has a COP equal to 0.8, that is in agreement with the results published by Guido et al [25]. Gomri [26] developed an analysis of a single and double effect absorption chiller, he reports that the COP of single effect is between 0.73 and 0.79 while double effect has COP between 1.22 and 1.42.

Heat exchangers HE1 and HE2, which recover energy from the primary and secondary circuits (hot water for sanitary purpose), were designed and simulated utilizing the NTU (number of thermal units) method. The design sanitary use flow is 6000 kg/h for both heat exchangers. HE2 is designed assuming that water enters at 22.2°C and leaves at 42°C and HE1 is designed assuming water enters at 30°C and leaves at 50°C (design condition). Sanitary use hot water recovers energy at HE2 and HE1 in a series arrangement [MS(I) = MP(I)]. Heat exchangers HE1 and HE2 design conditions should be defined to allow energy recovery at intermittent sanitary use hot water demand (figures 6 and 7) and engine part load condition. It's not the same condition of table 3 (trigeneration system full load energy balance).

Cooling towers are responsible to reject the absorber and condenser energy of the absorption chiller and to reject the unused engine secondary circuit energy. An air cooler is utilized to reject the unused primary circuit energy. Energy rejection equipment and auxiliary heat exchangers are responsible for rejecting system unused energy, allowing the engine to operate in accordance with the temperatures required by the manufacturer. Computational procedures for this equipment were introduced in the software COGMCI, but it will not be discussed in detail in this study. The total produced electricity is 2.5% higher than the net engine power, taking into account the use of electricity in auxiliary equipment (parasitic load – pumps, cooling tower and air cooler fan motors). No heat loss is assumed at the exhaust gas ducts and hot water pipes.

For the exergy analysis the ambient reference is set to T_0 = 25°C, and P_0 = 100 kPa.

The engine exergy consumption rate is calculated for the fuel standard chemical exergy (51,737 kJ/kg), assuming a natural gas composition of 90% CH_4, 8% C_2H_6 and 2% C_3H_8 [27-29].

5. ENERGY AND EXERGY EFFICIENCY

To evaluate the engine trigeneration system energy and exergy efficiency and to compare it to the separate production of electricity in centralized thermal plants, and chilled water (air conditioning) and hot water at site location, some equations are reviewed and defined in this section.

5.1 EUF and exergy efficiency

The energy utilization factor (EUF) is a common energy efficiency indicator, based on the first law of thermodynamics, utilized to evaluate cogeneration/trigeneration systems. It is defined as the ratio of the usable energy of the trigeneration system to the energy input. For a trigeneration system producing electricity, hot water and chilled water it can be calculated as:

$$EUF = \frac{\dot{W}_{net} + \dot{E}_{hw} + \dot{E}_{cw}}{\dot{m}_{fuel}\, LHV_{fuel}} \quad (1)$$

$$EUF = \frac{\dot{W}_{net} + \dot{m}_{12}(h_{15} - h_{12}) + \dot{m}_{16}(h_{16} - h_{17})}{\dot{m}_1\, h_1} \quad (2)$$

Exergy efficiency utilizes the second law of thermodynamics to evaluate the system efficiency. Exergy efficiency is defined as the ratio of exergy in the products to the exergy input. For a trigeneration system producing electricity, hot water and chilled water it can be calculated as:

$$\varepsilon = \frac{\dot{W}_{net} + \sum \dot{E}x_{flow}}{\dot{m}_{fuel}\, ech_{fuel}} = \frac{\dot{W}_{net} + \dot{E}x_{hw} + \dot{E}x_{cw}}{\dot{m}_{fuel}\, ech_{fuel}} \quad (3)$$

Where:

$$\dot{E}x_{flow} = \dot{m}[(h_e - h_i) - T_0(s_e - s_i)] \quad (4)$$

$$\dot{E}x_{hw} = \dot{m}_{12}[(h_{15} - h_{14}) - T_0(s_{15} - s_{14}) + (h_{13} - h_{12}) - T_0(s_{13} - s_{12})] \quad (5)$$

$$\dot{E}x_{cw} = \dot{m}_{16}[(h_{16} - h_{17}) - T_0(s_{16} - s_{17})] \quad (6)$$

Table 5 reveals the energy and exergy of the trigeneration system products: electricity, chilled water and hot water (recovered at PC and SC). Fig. 11 reveals the EUF and the exergy efficiency of the proposed trigeneration system, the results were obtained applying equations (1)-(6) using the thermodynamic properties of table 3.

Table 5 – Energy and exergy of the trigeneration products

	ENERGY		EXERGY	
	(kW)	(%)	(kW)	(%)
hot water SC	116.0406	4.20	2.503613	0.08
hot water PC	50.62838	1.83	4.454053	0.14
chilled water	966.7712	34.96	42.1684	1.34
steam	0	0.00	0	0.00
power	1,170	42.32	1,170	37.18
SUM	2303.44	83.31	1219.126	38.74

EUF is calculated as 83.31%. The trigeneration system produces 1170 kW of electricity (2.5% is parasitic load) with an energy input of 2765 kW, electricity contributes with 42.32%. As revealed in figure 10 and table 3, sanitary use hot water recovers energy at the engine primary and secondary circuit. Primary circuit contributes with 50.6 kW (1.83%) and secondary circuit with 116 kW (4.2%). Most of the engine energy is utilized at the absorption chiller, since 1204.87 kW is supplied to produce 966.8 kW of chilled water (absorption chiller COP is 0.8), chilled water contributes with 34.96%.

Exergy efficiency is calculated as 38.74%. Electricity contributes with 37.18%, hot water with 0.22% and chilled water with 1.34%. It's interesting to note that the hot water secondary circuit energy contribution is higher than the primary circuit, but the hot water primary circuit exergy contribution is higher than the secondary circuit, since the hot water produced recovering primary circuit energy (HE1) is at high temperatures than in the secondary circuit.

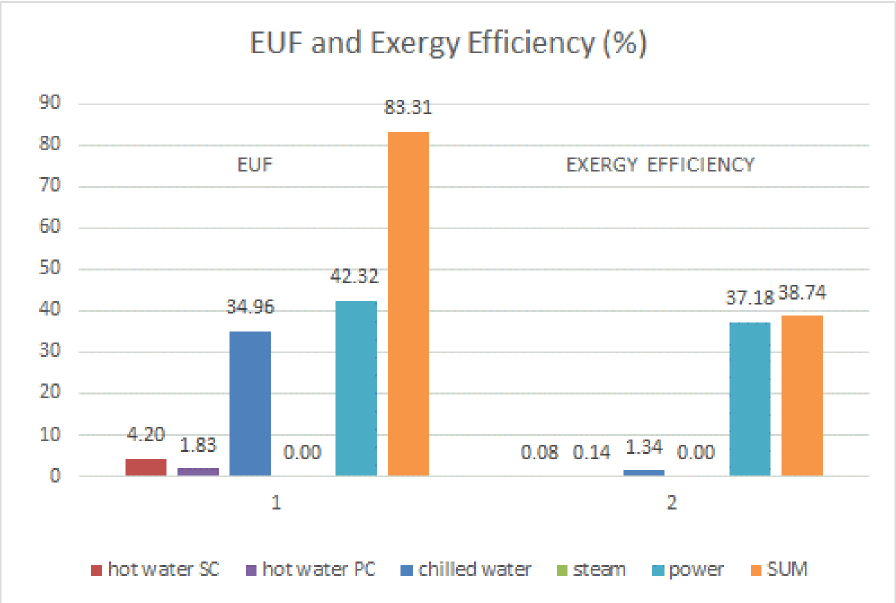

Figure 11 – EUF and Exergy Efficiency

5.2 Primary energy consumption and the equivalent thermal efficiency (ETE) criteria

Table 5 revealed the energy of the trigeneration products. Defining energy conversion efficiency allow the calculation of the primary energy input necessary to produce the same products with the same quantities produced by the trigeneration system.

To develop this analysis, three different scenarios for energy conversion efficiency is defined:

- Low efficiency scenario: centralized thermal plant thermal efficiency is 40%, electrical chiller COP is 3 and hot water fueled boiler efficiency is 70%.
- Medium efficiency scenario: centralized thermal plant thermal efficiency is 50%, electrical chiller COP is 4.5 and hot water fueled boiler efficiency is 80%.
- High efficiency scenario: centralized thermal plant thermal efficiency is 60%, electrical chiller COP is 6 and hot water fueled boiler efficiency is 90%.

Combustion boiler and steam generator efficiency is defined between 70% - 90%, which represent typical efficiency of boilers and steam generators. In real systems combustion boilers and steam generators can operate in an on/off mode or in a controlled flame mode. Both experiences transient operation, superficial losses, warm up periods after low demand, etc. The annual efficiency is normally lower than the equipment nominal efficiency.

Ashrae standard 90.1 [30] defines typical COP of electrical chillers taking into account the compressor type, chiller size, condenser type (air cooled or water cooled), etc. A minimum COP of 2.8 is defined for air cooled electrical chiller, a COP between 4.2 and 5.5 is defined for water cooled electrical chillers and a COP between 5 and 6.1 was defined for water cooled electrical centrifugal compressor chillers. Evans et al. [31] developed a case study utilizing a COP of 3.4 for electrical chillers. Electrical chillers performance is affected by the chilled water temperature, part load operation, air/water temperature entering the condenser, water flow in the evaporator, air/water flow in the condenser, etc. The COP is normally defined by a test condition adopted by the manufacturer.

ARI 550/590 2011 [32] defines a test condition for electrical chiller. ARI 560/92 [33] defines a test standard for absorption chiller and heating.

Centralized thermal plants normally operate at part load with lower than their nominal thermal efficiency. Graus et al. [34] studied thermal efficiency of centralized thermal plants in different countries, they reported that the weighted average efficiencies are 35% for coal, 45% for natural gas and 38% for oil-fired power generation.

Electrical grid loss occurs in transformers, circuit breakers, transmission lines, etc [35]. A 10% electrical grid loss means that a 50% thermal efficiency thermal plant operates as a 45% thermal efficiency power plant in a 0% electric loss grid. Electrical grid loss factor ($F_{gridloss}$) is calculated as: 1 – electrical grid loss. The electrical grid loss factor multiples the thermal efficiency. Decentralized electricity production has reduced electricity loss, since most of the electricity is consumed close to the generation site. Roselli et al [36] developed a study of different air conditioning systems for a building, they commented that accordingly with a TERNA report the average Italian efficiency of thermoelectric-based power plant was 44.7% in 2017, considering transmission and distribution losses.

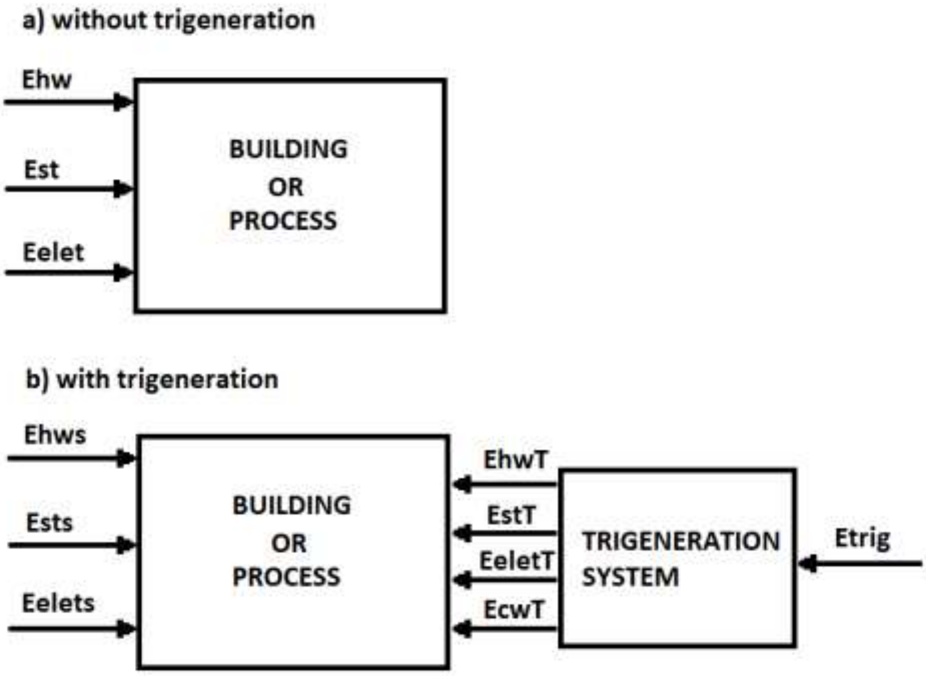

Figure 12 – building energy consumption without and with a trigeneration system

Figure 12a shows a building or process energy consumption (hot water, steam and electricity) without a cogeneration/trigeneration system. Total energy consumption is the sum of the hot water, steam and total electricity consumption (equation 7) – electrical chiller consumption is inserted at the total electricity consumption. Assuming energy conversion factors for electricity, hot water and steam, the PEC can be calculated using equation 8.

$$\dot{E}c = \dot{E}_{hw} + \dot{E}_{st} + \dot{E}_{elet} \quad (7)$$

$$PEC_{without} = \frac{\dot{E}_{hw}}{\eta_{hw}} + \frac{\dot{E}_{st}}{\eta_{st}} + \frac{\dot{E}_{elet}}{\eta_{elet}} \quad (8)$$

Figure 12b shows a building or process energy consumption with a cogeneration/trigeneration system. Cogeneration/trigeneration systems can provide total, a part or can export their products. Surplus energy can be necessary to meet hot water (equation 9), steam (equation 10) and the electricity (equation 11) consumption.

The total building/process electricity consumption can have a participation of electrical chillers. Trigeneration systems using absorption chillers replaces a part of this electricity consumption reducing the electrical chiller use. The electrical chiller reduced electrical consumption can be assumed as an avoided electricity consumption (equation 11). The avoided electricity consumption depends on the building/process cooling load that is being replaced by the absorption chiller use and the COP of the existing electrical chillers (equation 12).

$$\dot{E}_{hws} = \dot{E}_{hw} - \dot{E}_{hwT} \quad (9)$$

$$\dot{E}_{sts} = \dot{E}_{st} - \dot{E}_{stT} \quad (10)$$

$$\dot{E}_{elets} = \dot{E}_{elet} - \dot{E}_{eletav} - E_{eletT} \quad (11)$$

$$\dot{E}_{eletav} = \dot{E}_{cwT}/COP \quad (12)$$

Cogeneration/trigeneration systems energy consumption is the fuel mass flow multiplied by the fuel LHV. The energy products can be hot water, steam, chilled water and electricity (equation 13). Adopting the control volume as the building/process plus the trigeneration system, the control volume PEC can be calculated using equation 14, where the surplus hot water, steam and electricity can also be exported (minus sign should be used).

$$\dot{E}_{trig} = \dot{E}_{hwT} + \dot{E}_{stT} + \dot{E}_{cwT} + \dot{E}_{eletT} + \dot{E}_{losses} \tag{13}$$

$$PEC_{withTrig} = \frac{\dot{E}_{hws}}{\eta_{hws}} + \frac{\dot{E}_{sts}}{\eta_{sts}} + \frac{\dot{E}_{elets}}{\eta_{elets}} + \dot{E}_{trig} \tag{14}$$

Assuming that the PEC is the same with cog/trig (equation 14) and without cog/trig (equation 8), equations 8 and 14 can be matched, resulting in equation 15.

$$\frac{\dot{E}_{hw}}{\eta_{hw}} + \frac{\dot{E}_{st}}{\eta_{st}} + \frac{\dot{E}_{elet}}{\eta_{elet}} = \frac{\dot{E}_{hws}}{\eta_{hws}} + \frac{\dot{E}_{sts}}{\eta_{sts}} + \frac{\dot{E}_{elets}}{\eta_{elets}} + \dot{E}_{trig} \tag{15}$$

Assuming that hot water, steam and electricity production efficiency is the same for the building/process without a cog/trig system and with a cog/trig system and rearranging equation 15:

$$\frac{\dot{E}_{hw} - \dot{E}_{hws}}{\eta_{hw}} + \frac{\dot{E}_{st} - \dot{E}_{sts}}{\eta_{st}} + \frac{\dot{E}_{elet} - \dot{E}_{elets}}{\eta_{elet}} = \dot{E}_{trig} \tag{16}$$

$$\eta_{elet} = \frac{\dot{E}_{elet} - \dot{E}_{elets}}{\dot{E}_{trig} - \left(\frac{\dot{E}_{hw} - \dot{E}_{hws}}{\eta_{hw}} + \frac{\dot{E}_{st} - \dot{E}_{sts}}{\eta_{st}}\right)} = ETE \tag{17}$$

Equation 17 can be interpreted as the thermal pant efficiency at which PEC without a cog/trig system and with a cog/trig system is the same. This thermal efficiency is defined as the equivalent thermal efficiency (ETE).

To take into account electricity losses in the distribution grid, the electricity grid loss factor is inserted at equation 17, and the equivalent thermal efficiency with electricity grid loss (ETE_{GL}) is defined.

$$\eta_{elet} = \frac{\frac{\dot{E}_{elet} - \dot{E}_{elets}}{F_{gridloss}}}{\dot{E}_{trig} - \left(\frac{\dot{E}_{hw} - \dot{E}_{hws}}{\eta_{hw}} + \frac{\dot{E}_{st} - \dot{E}_{sts}}{\eta_{st}}\right)} = ETE_{GL} \tag{18}$$

Different hot water and steam efficiencies can also be assumed in equation 15, resulting in a different ETE equation (not shown here). Electricity, steam and hot water exports can also be evaluated with equation 15.

Equation 17 can be rearranged to equation 19 assuming that no surplus energy is necessary and combining with equations 9, 10 and 11. The same steps can be applied to equation 18, resulting in the ETE with grid loss (equation not shown).

$$\eta_{elet} = \frac{\dot{E}_{eleT} + \dot{E}_{eletav}}{\dot{E}_{trig} - \left(\frac{\dot{E}_{hwT}}{\eta_{hw}} + \frac{\dot{E}_{stT}}{\eta_{st}}\right)} = ETE \qquad (19)$$

Equation 19 allows the calculation of the equivalent thermal efficiency of a process / building that uses all the engine trigeneration system products with no surplus energy consumption – design energy balance. Figure 13 reveals the ETE for the low, medium and high efficiency scenario assuming no grid loss, 10% grid loss and 20% grid loss – calculated using equation 19.

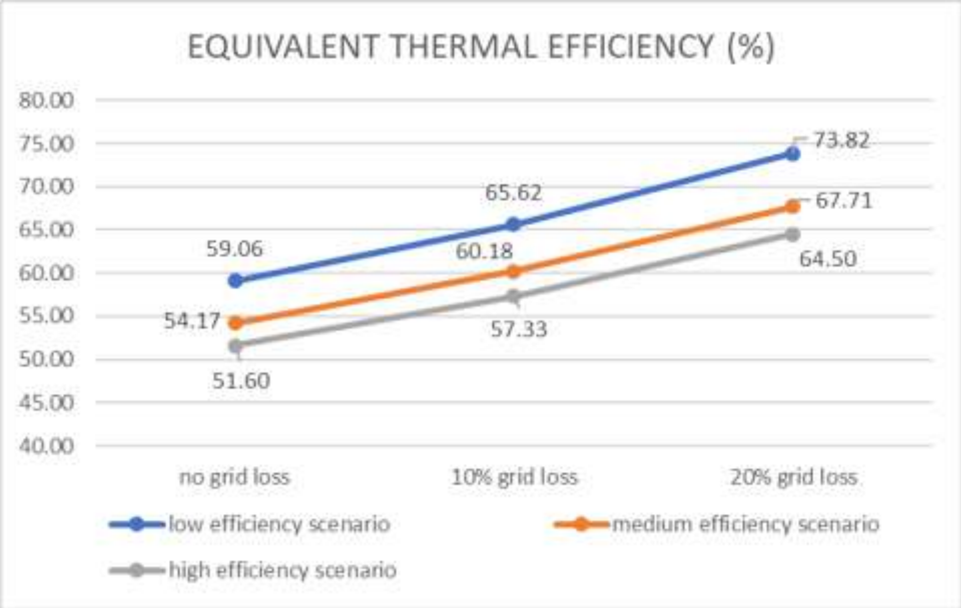

Figure 13 – equivalent thermal efficiency x grid loss – design energy balance

Assuming the low efficiency scenario with 10% grid loss, the ETE is calculated as 65.62%. It means that if the country average centralized thermal plant efficiency is lower 65.62% the proposed trigeneration system can save primary energy. If it is 65.62% no PES will occur and if it is higher than 65.62% the project will decrease the country average thermal efficiency.

6. SIMULATION RESULTS

At this section the proposed cog/trig system (figure 10) is simulated attending the hospital building eight groups energy demand.

6.1 Electricity

Figure 14 (summer and autumn) and figure 15 (winter and spring) shows the electricity demand and production obtained through the simulation analysis. The electricity demand presented at these figures is different than the values presented in figures 2 and 3, since at figures 14 and 15 the electricity demand is corrected due to the avoided electricity demand replaced by the use of the absorption chilled instead of the electrical chillers.

At summer weekdays at hour 10 the electricity demand is 1860 kW (figure 2) and the cooling load is 280.6 RT (figure 4). The corrected demand is calculated as 1646 kW (1860 kW – 273.5x0.7822), where 273.5 RT is the absorption chiller chilled water production and 0.7822 is the electrical chiller efficiency in kW/RT (COP=4.5 =3.52/0.7822). The avoided electricity demand due to the absorption chiller use is 214 kW.

In summer the engine is expected to operate at part load between hours 0 to 6 and 20 to 23 at weekdays and at all weekend hours. At the remaining hours it operates at full load. If the electricity demand exceeds the engine full load power output surplus electricity should be bought from the grid.

In autumn the engine is expected to operate at part load between hours 18 and 7 at weekdays and at all weekend hours.

In winter the engine is expected to operate at part load between hours 19 and 7 at weekdays and at all the weekends hours.

In spring the engine is expected to operate at part load between hours 18 and 6 at weekdays and at all the weekends hours.

Figure 16 reveals the expected engine load factor for the eight data groups. The lower engine load factor is close to 60% and an average engine load of 85.75% is expected to occur during the year operation period.

6.2 Sanitary use hot water

Hot water is produced recovering energy from the engine secondary circuit (low temperature intercooler – figure 10). When the engine operates at full load about 4.19% of the engine energy is available at the secondary circuit (~ 116 kW). Engine secondary circuit energy is planned to be used to attend the hospital sanitary hot water demand (HE2), but the hospital hot water energy demand and temperature (50ºC) is higher than the secondary circuit water design data [flow 8 to 11], then additional energy of the PC is recovered at HE1.

Hot water demand and production can be compared at figure 17. It can be noted that the sanitary use hot water demand is expected to be attended by the engine trigeneration system (lines are coincident). Hot water demand is not met at hours 13 and 14 at summer weekends since (i) the engine operates at part load, (ii) PC water entering HE1 [flow 4] is at a lower temperature than in the design mode – 80.35ºC at hour 13 and 80.36ºC at hour 14 and few energy is recovered at HE1 since flow 5 should not be lower than 80ºC (design condition – table 3).

Figure 18 reveals the sanitary use hot water temperature leaving HE2 (SC heat exchanger). Design SC water temperature leaving the engine is 43ºC [flow 8 – table 3], but at the engine part load operation sanitary use hot water demand temperature is lower, limiting the temperature of the sanitary use hot water leaving HE2 [flow 13]. At all hours surplus energy needs to be recovered at HE1 (PC heat exchanger) to reach the design sanitary use hot water demand temperature [flow 15].

6.3 Absorption chiller (AC) / cooling load

The AC capacity and the hospital cooling load can be compared at figure 19 (summer and winter). The absorption chiller produces about 275 RT (967 kW) with the engine at full load. In summer the electrical chiller needs to operate between hours 9 to 18 at weekdays and between hours 13 and 16 at weekends. At the remaining hours of the year the absorption chiller can met the hospital cooling load. The autumn and spring figure are not shown in the paper.

Figure 20 reveals the primary circuit hot water temperature in winter weekdays. It can be noted that at all hours the water temperature leaving the engine [flow 2] and the water temperature leaving the EGHE [flow 3] is lower than at the design condition, since the engine operates at part load at these hours. The figure also reveals that the primary circuit water temperature leaving the absorption chiller [flow 4] is higher than in the design condition, since part of the hot water flow [flow3] entering the absorption chiller generator is being by-passed to adjust chiller water production to the chiller water demand (cooling load). Higher primary circuit hot water temperatures leaving the absorption chiller [flow 4] are verified at hours 8 to 10 since the engine is at a high load factor and the cooling is relatively low. At hors 14 to 16 flow 4 temperature is reduced since the cooling load is high and more energy is recovered at the absorption chiller.

The temperature difference between flow 4 and flow 5 is due to the energy recovery at HE1 to reheat sanitary use hot water demand to the design condition [flow 15]. In the first day hours they are almost coincident, since the sanitary use hot water demand is close to zero. At hour 9 the sanitary use hot water has a peak consumption and the difference between the temperature of flow 4 and 5 is close to 2ºC (close to 90 kW is recovered at HE1). A higher difference can also be verified at hour 15.

The temperature difference between flows 4 and 5 are not so evident since the PC has about 1254 kW while the sanitary use hot water demand is between 0 and 218 kW (figure 17) but a part of it is attended by SC energy at HE2. HE1 has a maximum energy recovery of 102 kW at winter weekdays hour 9.

PC hot water enters the engine at 80ºC [flow 7], if the primary circuit hot water temperature is higher than 80ºC [flow 5], energy needs to be rejected at the PC air cooler.

SC hot water enters the engine at 40ºC [flow 11], if SC hot water temperature leaving HE2 [flow 9] is higher than 40ºC, energy needs to be rejected at the SC cooling tower (figure not shown).

6.4. Energy Utilization Factor (EUF)

The EUF is calculated using equation 1. Figure 21 reveals the eight EUF groups results. The net electricity contribution to EUF varies between 39.84% (hour 5 at winter weekdays) and 42.3% with engine at full load (engine full load efficiency 43.4% is multiplied by 0.975 to account for the parasitic loads). Hot water contribution to EUF is close to 0% at hours there is a small hot water demand (initial day hours) and has a maximum value of 8% in winter weekdays hour 9 (maximum hot water demand – 6750 kg/h or 1.875 kg/s). The chilled water production at the absorption chiller contributes between 16.32% in winter weekdays hour 8 and 37.1% in summer weekdays hour 4.

The absorption chiller contribution is higher at summer weekdays hour 4 (37.1%) than at design condition (34.96%) since at this hour the engine operates at part load (79.44%), more energy is available at the exhaust gases (compared to the engine 100% load) and the water temperature leaving the absorption chiller (flow 4 is at 80.4ºC) is closed to the water temperature entering the engine [flow 7 – 80ºC] than in the design condition (flow 4 at design condition is at 81.08 ºC – table 3).

The higher EUF is 82.19% achieved at summer weekdays hour 14. Electricity contributes with 42.35%, hot water at HE2 with 3.04%, hot water at HE1 with 1.31% and chilled water with 35.49%. At this hour the engine operates at full load, sanitary use hot water demand is 3.64 m3/h and the cooling load is higher than the absorption chiller production (all the absorption chiller production is being used).

The lower EUF is 61.8% and occurred at winter weekdays hour 7. At this hour the electricity contributes with 41.65%, hot water at HE2 with 2.25%, hot water at HE1 with 0.88% and chilled water with 17.03%. The engine operates with 86.6% load, sanitary use hot water demand is 2.36 m3/h and the cooling load is just 117.85 RT (414.8 kW). This low EUF result is a combination of engine load, sanitary use hot water demand and cooling load. PC temperature profiles at winter reveals that close to 50% of the PC and exhaust gas energy is being rejected (figure 20).

An average annual EUF of 72.3% was calculated.

6.5. Exergy Efficiency

The exergy efficiency of the trigeneration system is revealed at figure 22. Exergy efficiency is calculated using equation 3. Exergy efficiency results are between 39.3% and 35.24%. The engine electricity production efficiency is the main factor to justify figure 22 curves shape.

Better results are obtained in summer weekdays, a maximum value of 39.3% was calculated at hour 14, electricity contributes with 37.21%, hot water with 0.08% and chilled water with 2.0%. The exergy flows were calculated utilizing the dry bulb temperature profile of figure 8. At hour 14 the maximum dry bulb temperature is verified (29.45ºC), and the chilled water contribution is even higher than in the design condition (figure 11), resulting in an exergy efficiency higher than in the design condition.

The lower exergy efficiency was verified at winter weekdays hour 5 - 35.24%. Electricity contributes with 35.03%, hot water with 0% and chilled water with 0.22%. At this hour hot water demand is zero and the dry bulb temperature is at a lower value, reducing the chilled water contribution.

The results reveal the influence of the adoption of a variable thermodynamic dead state (dry bulb temperature profile of figure 8) in the maximum and minimum exergy efficiency values.

The annual mean exergy efficiency was calculated as 37.51%.

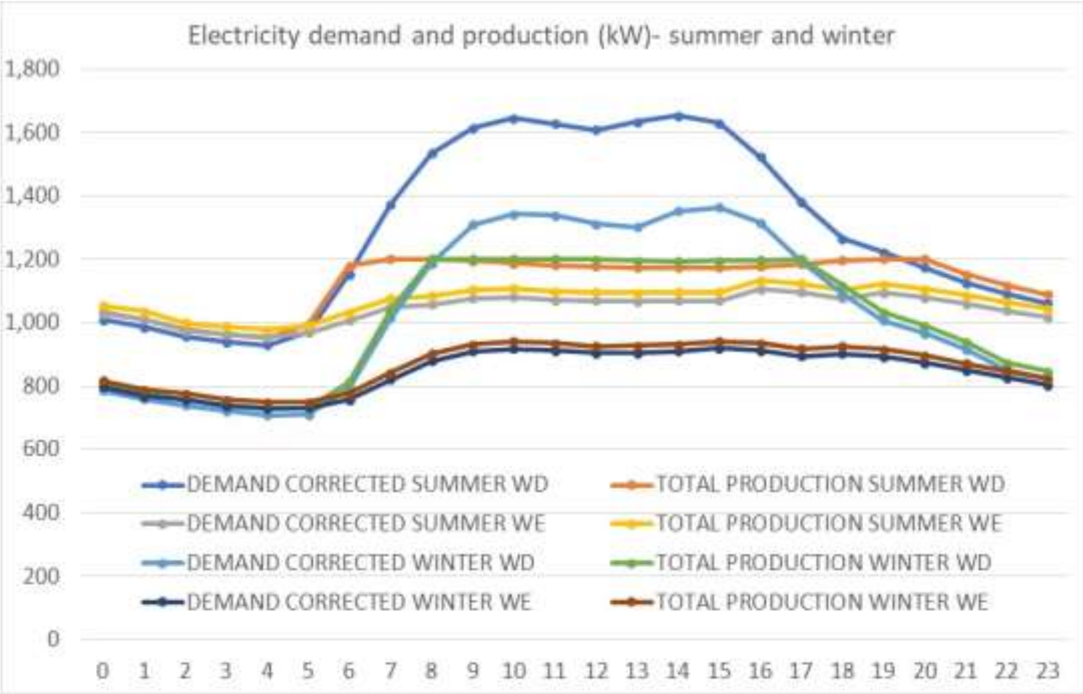

Figure 14 – Electricity demand and production – summer and autumn

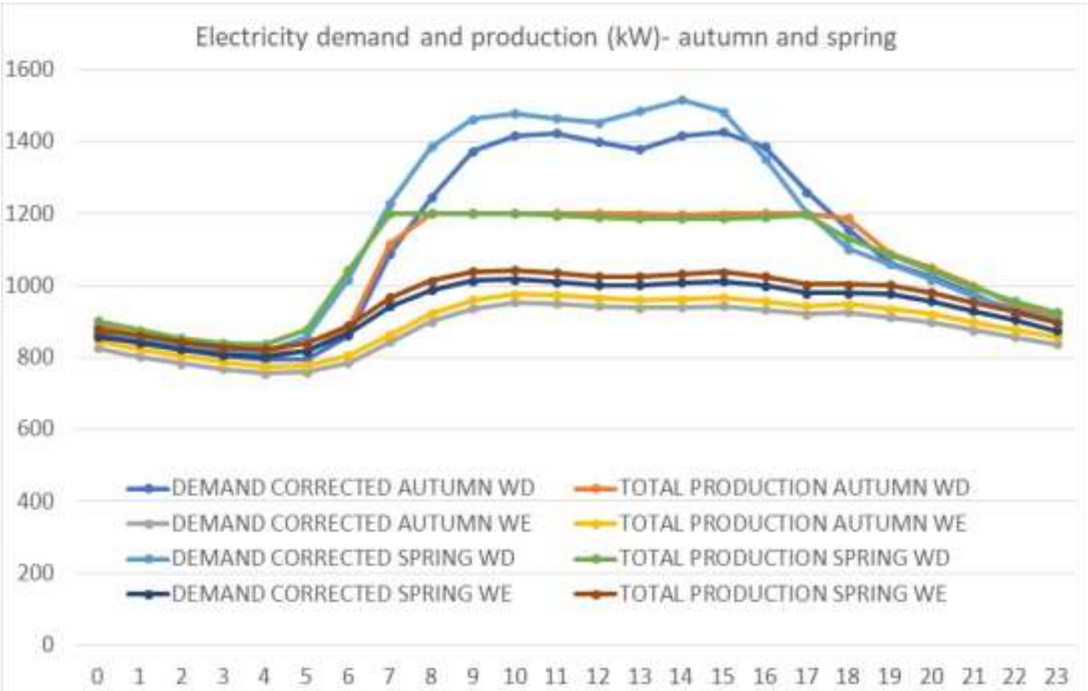

Figure 15 – Electricity demand and production – winter and spring

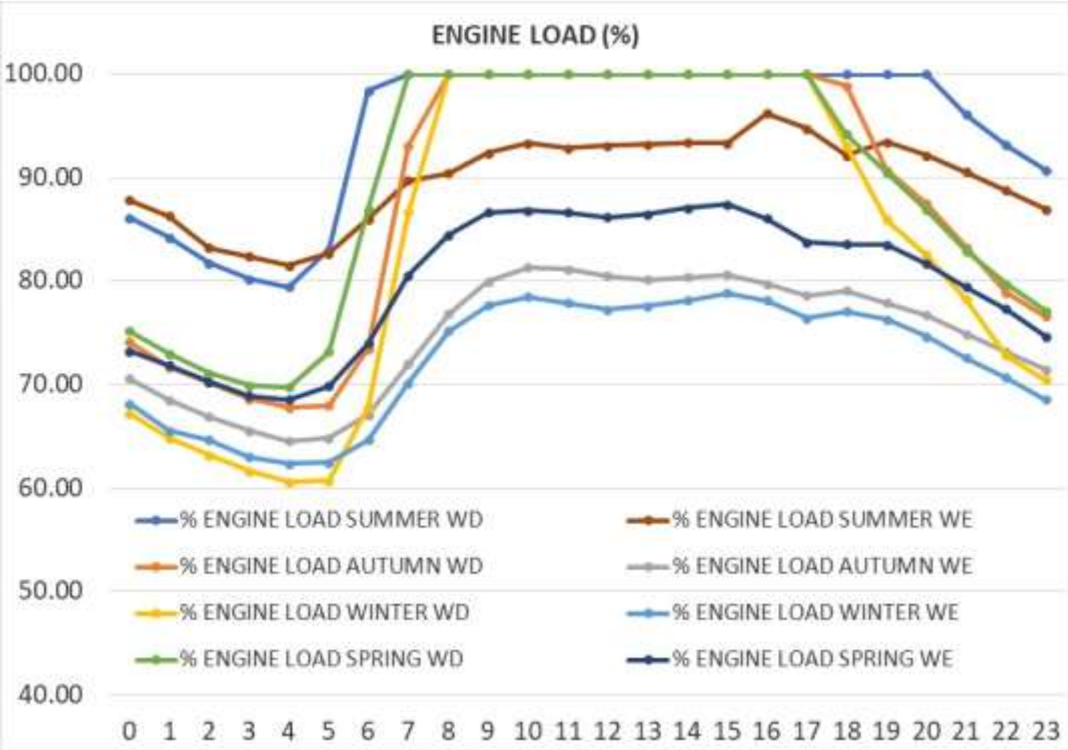

Figure 16 – Engine load

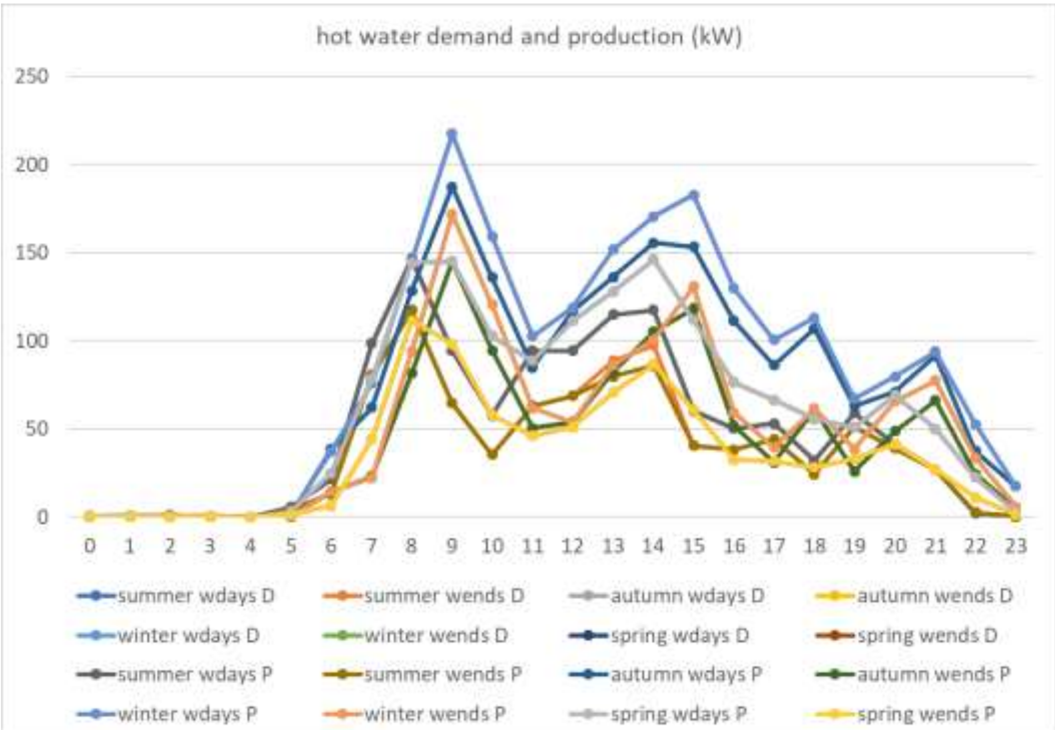

Figure 17 – Hot water demand (kW)

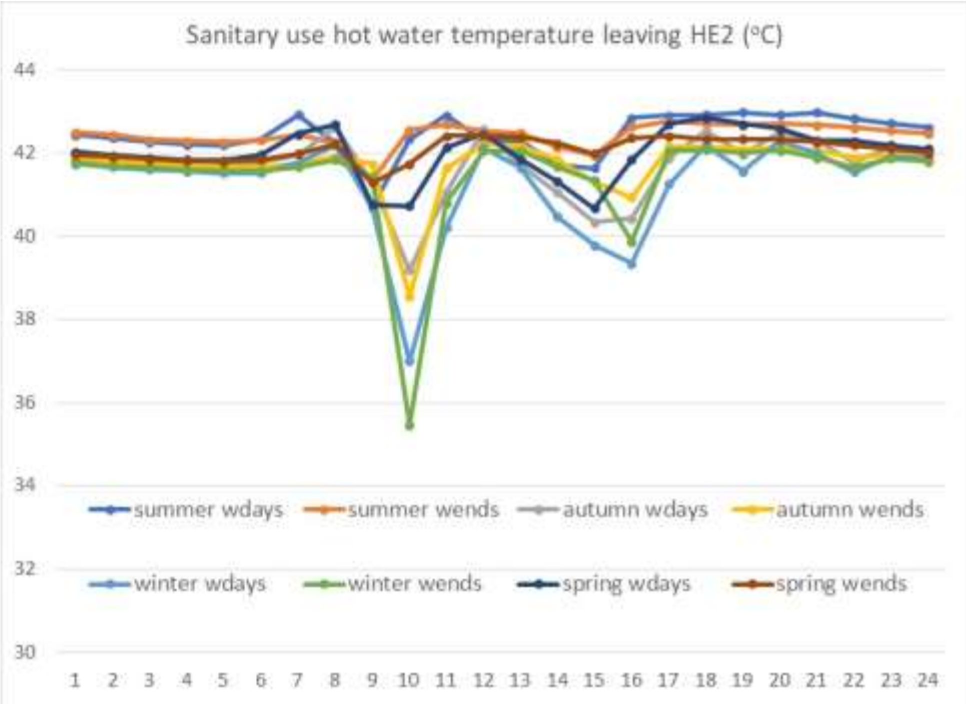

Figure 18 – sanitary use hot water temperature leaving HE2 (ºC)

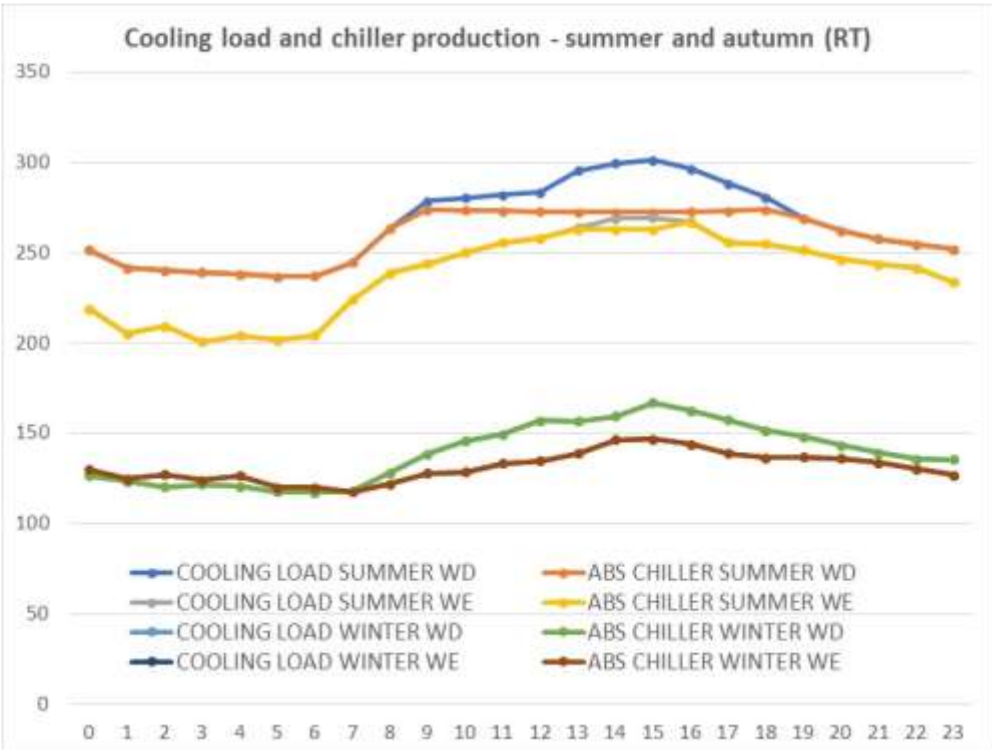

Figure 19 – cooling load and chiller production (RT)

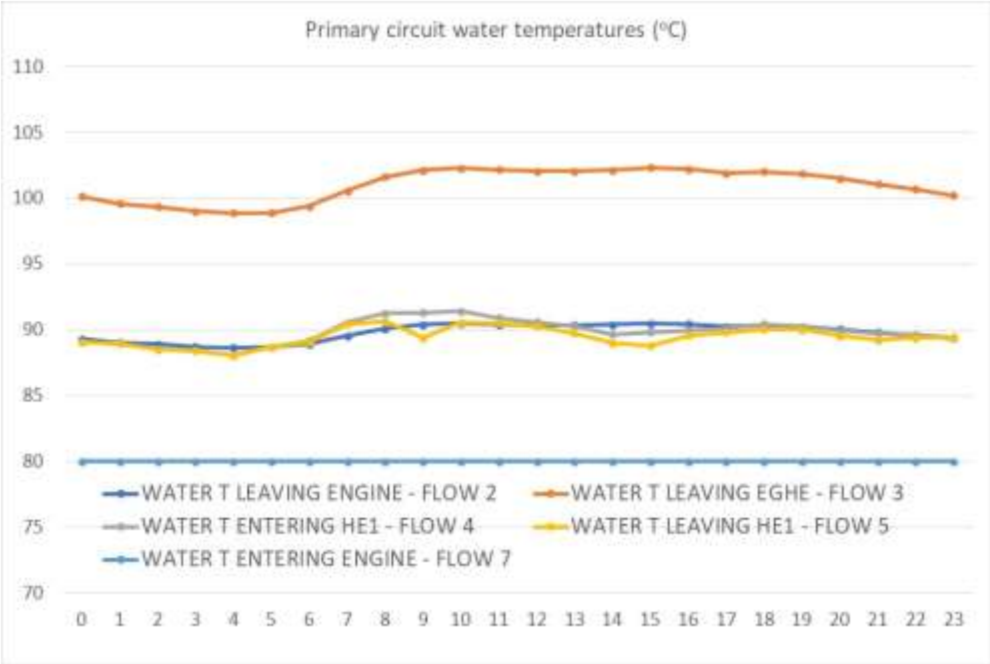

Figure 20 – primary circuit water temperatures (ºC) – winter weekends

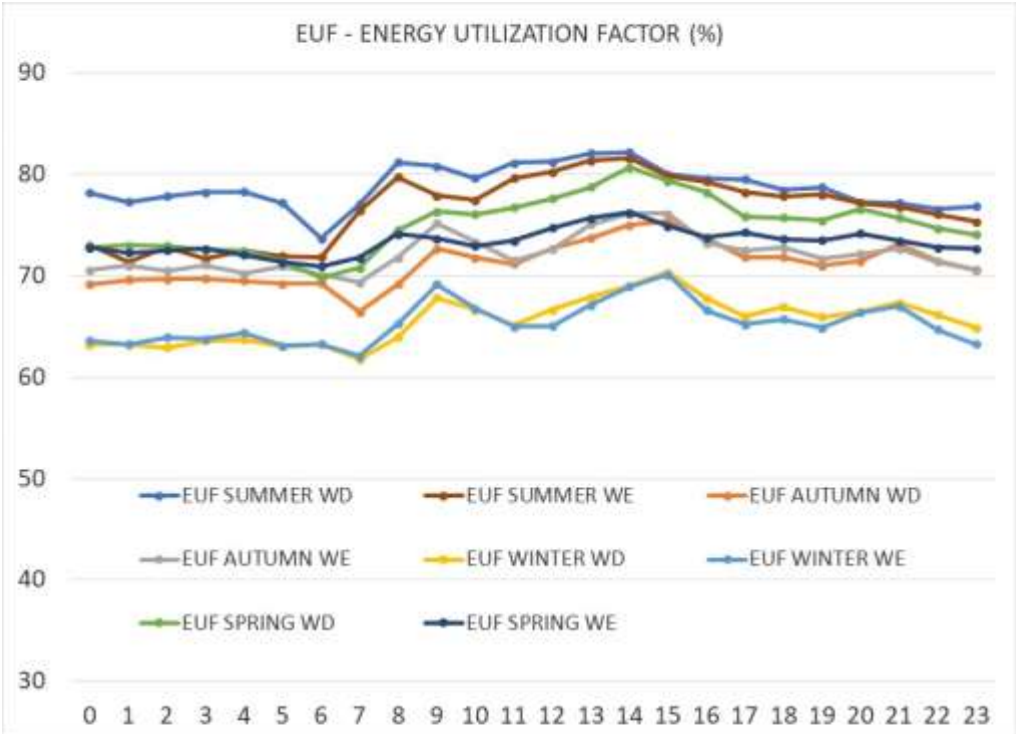

Figure 21 – EUF

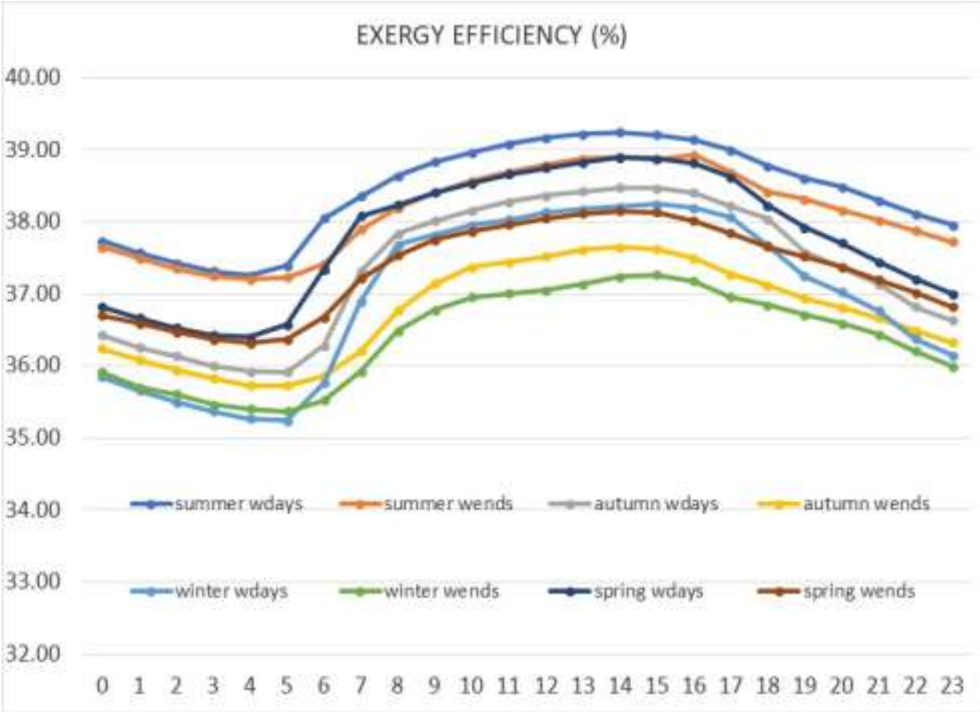

Figure 22 – Exergy efficiency

6.6. Annual Energy Analysis

At table 2 the hospital average electricity and hot water consumption for the eight demands profiles (figures 2 to 7) were revealed. The annual consumption divided by the efficiency conversion reveals the primary energy consumption (PEC).

Table 6 reveals the energy summary of the proposed trigeneration system attending the energy demands profiles. Line 1 reveals the eight groups daily electricity demand. Line 2 reveals the corrected electricity demand (takes into account the absorption chiller use instead of the electrical chillers) Line 3 reveals the net electricity production and line 4 the grid electricity consumption (surplus electricity).

Line 5 reveals the sanitary use hot water demand and line 6 reveals the amount of energy recovered at HE2. Line 7 reveals the energy recovered at HE1. Line 8 reveals the necessary surplus energy to warm the sanitary use hot water to the design condition (50ºC). Line 9 reveals the daily natural gas consumption.

TABLE 6 – TRIGENERATION DAILY ENERGY BALANCE (kWh/day and kWh/year)

	Daily Analysis with COG / TRIG	**summer wd**	**summer we**	**autumn wd**	**atumn we**	**winter wd**	**winter we**	**spring wd**	**spring we**	annual
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	summary (kWh/year)
1	ELECTRICITY DEMAND (kWh/day)	35970.1	29544.414	30129.832	24318.641	27519.135	22779.24	31683.057	26110.535	10771365.49
2	ELECTRICITY DEMAND CORRECTED (kWh/day)	31105.006	25086.075	26641.436	20981.19	24905.948	20314.139	27579.727	22409.259	9434795.595
3	NET ELECTRICITY PRODUCTION (kWh/day)	26431.758	25086.075	24604.809	20981.19	23572.789	20314.139	24869.612	22409.259	8770091.407
4	ELECTRICITY CONSUMPTION (kWh/day) - GRID	4673.248	0	2036.627	0	1333.159	0	2710.115	0	664704.188
5	hot water Demand SC (KWh/day)	1171.848	901.708	1788.266	1085.804	2020.538	1241.727	1480.475	842.297	525258.002
6	hot water PRODUCTION SC HE2 (KWh/day)	842.204	651.576	1228.342	746.736	1336.709	822.01	1042.023	602.137	361915.908
7	hot water PRODUCTION PC HE1 (KWh/day)	329.637	229.722	559.928	339.07	683.833	419.715	438.453	240.161	162750.403
8	surplus hot water demand (kWh/day)	0.007	20.41	-0.004	-0.002	-0.004	0.002	-0.001	-0.001	591.691
9	FUEL CONSUMPTION (kWh/day)	62783.7797	59999.9899	58947.5446	51283.4091	56729.7567	49850.5984	59501.4233	54329.3631	21067049.13

The last column of table 6 reveals the annual results – daily results (group data) are multiplied by the number of days in each group and the eight data groups are summed.

Trigeneration primary energy consumption (PEC) attending the hospital building energy demands is the engine energy input (last column of line 9) plus the energy demands that aren't attended by the trigeneration and needs to be purchased or produced. Surplus electricity (664,704.2 kWh/year – last column at line 4) is bought from the grid and surplus hot water (591.7 kWh/year – last column at line 8) needs to be produced at existing boilers.

The above results are used at equation 18. Figure 23 results reveals ETE of the proposed trigeneration system. ETE between 47.7% and 66.6% were calculated, depending on the existing efficiency scenario (low, medium and high) and the electricity loss in the existing grid.

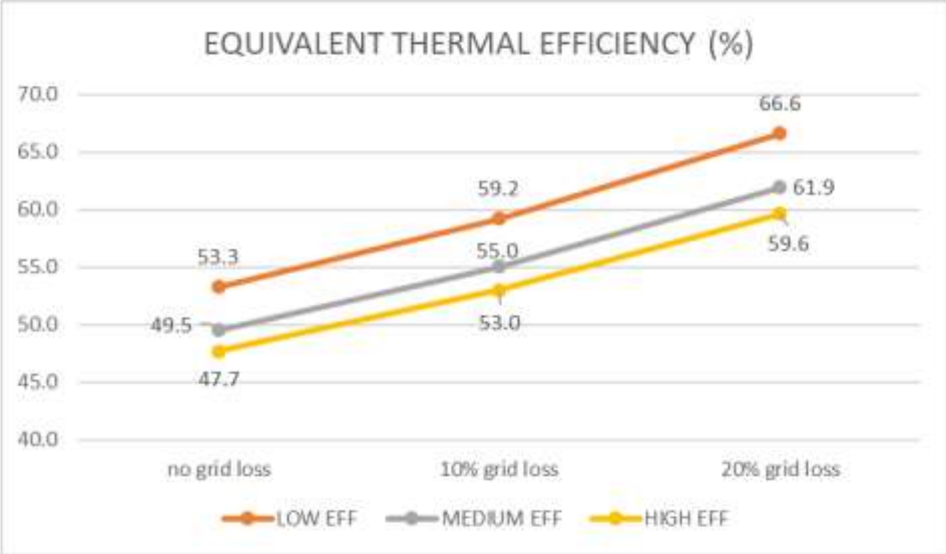

Figure 23 – equivalent thermal efficiency x grid loss– attending hospital energy demands

Figure 23 results can be compared to figure 13 results. The simulated results (figure 23) are lower than the design energy balance results (figure 13), since the design energy balance assumes that all the trigeneration products are being used and no surplus energy is necessary for the building/process. The simulation results compute the trigeneration energy at a given hour and simulate the engine, the EGHE, the heat exchangers (HE1 and HE2) and the absorption chiller performance attending the building energy loads. The results reveal how much energy can be recovered, the necessary surplus energy and the unused energy (rejected).

7. Other Engines Results

To evaluate the influence of different engines (power, efficiency, temperatures, energy balance, etc) and operational modes on the attractiveness of the proposed trigeneration systems in a tropical climate, the methodology presented at this study and the simulation developed at section 6 was repeated for eight different cases.

Engines 1 to 5 (table 4) and their design data (PC and SC temperatures, electric efficiency, energy balance and part load performance curves) are utilized.

The following cases were investigated:

- Case 1: 400 kW (engine 4) at electric dispatch at the low, medium and high efficiency scenario.
- Case 2: 600 kW (engine 3) at electric dispatch at the low, medium and high efficiency scenario.
- Case 3: 800 kW (engine 2) at electric dispatch at the low, medium and high efficiency scenario.
- Case 4: 1,200 kW (engine 1) at electric dispatch at the low, medium and high efficiency scenario.
- Case 5: 1,200 kW (engine 1) at full load at the low, medium and high efficiency scenario.

- Case 6: 1,200 kW (engine 1) at electric dispatch at summer, 70% engine load in autumn, 50% engine load in winter and 80% engine load in spring at the low, medium and high efficiency scenario.
- Case 7: 1,560 kW (engine 5) at electric dispatch at the low, medium and high efficiency scenario.
- Case 8: 1,560 kW (engine 5) at full load at the low, medium and high efficiency scenario.

The main results are summarized at table 7.

Line 1 shows the annual hospital electricity consumption (it is the same for all cases). Line 2 reveals the hospital corrected electricity consumption assuming the avoided electricity use in the electrical chillers due to the absorption chiller use – the corrected electricity demand depends on the absorption chiller production capacity (simulation analysis) and the COP of the existing electrical chillers. Line 3 reveals the trigeneration system net electricity production and line 4 the surplus electricity that needs to be bought from the grid. The corrected electricity consumption is lower in the low efficiency scenario (in a same engine analysis, for example case 1 - columns 3 to 5), since the COP of the electrical chiller is lower and more electricity consumption is replaced by the absorption chiller use. Higher engines produce more capacity in the absorption chillers and more electricity use is avoided due to the absorption chiller use (lower corrected electricity consumption – line 2). Cases 4 to 6 has almost the same corrected electricity consumption since they almost met the cooling load in almost all year, even when the engine operates at a reduced load (case 6). Cases 7 and 8 completely met the cooling load – corrected electricity consumption is the same. Line 17 shows the engine fuel consumption (natural gas – kWh/year) and line 18 shows the grid electric consumption (kWh/year).

Cases 7 and 8 meet all the cooling load and almost all the hot water demand, independent of the efficiency scenario. Case 7 at the low efficiency scenario exports more electricity to the grid than imports, since at low efficiency scenario more electricity is replaced by the absorption chiller use and the software limits the engine load to a minimum of 50%.

The annual hot water energy consumption is revealed at line 5. Hot water energy production at the SC circuit (HE2) is revealed at line 6. Line 7 shows the energy recovery in the PC (HE1). Line 8 reveals the necessary surplus energy to attend the annual sanitary use hot water consumption. Bigger engines cog/trig systems reject more energy in HE2 and HE1 and reduces the fuel use in boilers to attend the sanitary use hot water consumption.

Line 9 reveals the annual EUF. EUF is higher in small engines, since less energy is being rejected at air cooler and cooling tower. Case 5 and 8 reveal to have the lower EUF, since they operate at full load all the time (export electricity to the grid) and more energy is being rejected, due to variable energy demands (cooling load and sanitary use hot water). Case 6 revealed to be the 3rd better EUF since the engine operates at defined loads (autumn, winter and spring) and a good match of the engine residual energy and the hospital building energy demand is verified.

Line 10 reveals the annual exergy efficiency. Average exergy is almost equal at cases 1 to 3, since the engine has almost the same electrical efficiency. The differences are associated with the absorption chiller production and the hot water production due to different energy balance and SC and PC water temperatures. Case 5 has a higher average annual exergy efficiency, since the engine operates at full load at a higher electrical efficiency and electricity has the large contribution in the exergy efficiency. Case 6 is the lower average annual exergy efficiency, since the engine operates at part load at a reduced electrical efficiency. Case 6 annual exergy efficiency is higher in the high efficiency scenario (column 20) since at the high efficiency scenario the corrected electricity consumption is higher (line 2) and the engine produces more electricity with a higher electrical efficiency at a higher engine load (summer).

Line 11 reveals the average annual engine load, it is 100% for cases 1, 2, 5 and 8, almost 100% for case 3 and between 66.26 and 87.8% for cases 4, 6 and 7. Case 4 and 7 have the lower average annual engine load, being able to export electricity to the grid.

Cases 1, 2 and 3 operates at the building base electricity load and cases 4 to 8 are oversized systems (can export electricity do the grid).

Lines 13 and 14 reveals the electricity and hot water efficiency for the low, medium and high efficiency scenarios. Line 15 calculates the hospital building PEC (without a trigeneration system) at the low, medium and high efficiency scenarios (line 1 is divided by line 13 and summed to line 6 divided by line 14).

Line 20 reveals the hospital building PEC assuming that the cog/trig system was adopted (line 17 + line 18 divided by line 13 + line 19 divided by line 14). The lower PEC is verified at case 1 at the high efficiency scenario, since the engine operates at the base load and surplus energy is produced with high efficiency boilers and thermal plants. The second lower PEC is achieved by case 8 at the low efficiency scenario, revealing that at the low efficiency scenario the electricity export to the grid is a good opportunity.

Lines 22 to 24 reveals the ETE for the eight cases under the low, medium and high efficiency scenario assuming no grid loss, 10% grid loss and 20% grid loss. ETE between 45.86% and 68.98% were calculated. Higher ETE is verified for the lower engine (case 1), but cases 4 and 6 have almost the same ETE with the possibility to export electricity to the grid.

Some simple checks can be done. Line 26 reveals the engine average annual efficiency – line 3 is divided by line 17 (part load operation, parasitic load and ambient temperature influences the results). Line 27 reveals the annual average engine power production – line 3 divided by 8760 hours. Line 28 reveals the percentage reduction between the corrected electricity consumption (line 2) and the building electrical consumption without cog/trig (line 1) – how much electricity is avoided by the absorption chiller use.

8. Results and discussion

An annual average EUF between 62.59% and 80.96% and an average exergy efficiency between 35.98% and 38.14% were calculated. ETE between 45.86% and 68.98% was revealed. The results are in good agreement with the results obtained by other authors.

Wang et all [37] evaluated an engine CCHP system an energy efficiency between 57.9 and 89.5% was calculated depending on the energy recovery. Calise et al [38] evaluated three different strategies of an engine trigeneration system for an Italian hospital, global efficiencies between 75.6% and 90.3% were calculated. Wang et al [39] evaluated an engine trigeneration system with different fuels, efficiencies between 55 and 85% were revealed, depending on the fuel and the engine load. Wang et al [40] evaluated the use of hydrogen in an engine trigeneration system using the Eclipse software, efficiencies between 55 and 85% were predicted.

Low efficiency scenarios reveal a good opportunity for bigger engines trigeneration systems and the electricity export to the grid since the trigeneration PEC is lower for cases 8, 5, 4 , 6 and 7 respectively. In a medium efficiency scenario cases 1 to 6 revealed a similar PEC, while high efficiency scenarios favored lower engines – cases 1, 2 and 3 (Line 20 – table 7).

Exergy efficiency has a high participation of the electricity and revealed to be higher with a high efficiency engine (engine 1) operating at full load (case 5) – engine 1 full load electrical efficiency is 43.4%. The higher exergy efficiency solution was the lower EUF and ETE solution.

Higher EUF was achieved by case 1, since the trigeneration system operates at the base of the energy demands and a high fraction of the engine residual energy is recovered to meet the building loads. The ETE analysis revealed that cases 1, 2 and 6 are the best solutions, respectively. Case 6 is able to export 457 MWh/year (high efficiency scenario) or 1,459 MWh/year (low efficiency scenario) of electricity to the grid (line 18 – table 7) when operating at full load (case 5). Opting for cases 4 or 6 allows the cog/trig system electricity export in an intermittent electricity production grid (big share of solar photovoltaics and wind turbines) with a high ETE (47.66% to 65.35%). Case 6 fixed engine loads in autumn, winter and spring were defined looking to attend the cooling load - corrected electricity consumption (line 2) is almost the same for cases 4, 5 and 6. Case 6 needs more surplus sanitary use hot water than cases 4 and 5 (line 7).

Case 7 and 8 have higher power engines with the lower EUF and ETE, revealing that less residual engine energy was recovered. Case 8 exports between 3,530 and 4,538 MWh/year of electricity to the grid, depending on the efficiency scenario (line 18).

Assuming grid loss engine cog/trig systems can be the best available technology for natural gas use. Taking the Italy case as an example [36] all the solutions presented at this study have higher ETE than the average thermal efficiency reported in 2017 – 44.7%.

9. Conclusion

A detailed simulation methodology utilizing mean profiles of energy demands and climatic data for weekdays and weekends for the different season of the year was developed to predict the performance of a trigeneration solution in a hospital located at a tropical city. Tropical climate means warm to hot temperatures year-round, normally no space heating is necessary. The use of eight average energy demand curves and four average DBT and RH weather curves results in an error in the annual analysis, in a next paper the results of this study will be compared to an 8760 hours analysis.

Due to the hospital energy demand and installed equipment, an engine trigeneration configuration producing electricity, hot water and chilled water was proposed.

The software allows engine cogeneration / trigeneration developers to evaluate their projects and policy makers to develop strategies to rise country average thermal efficiency (reduce CO_2 emissions).

A complete understanding of the results requires a detailed results evaluation, the author discussed the best and the worst calculated value and also some observed tendencies.

The benefit of cog/trig systems depends on the site existing equipment technology and the country electricity production scenario as well as the existing electricity grid loss. Countries should evaluate their average thermal efficiency and their electricity grid loss.

Table 7 results reveals that engine cog/trig system can be a good opportunity to (i) rise the country installed capacity, (ii) rise the country average thermal efficiency, (iii) contribute to a stabilized grid (exporting electricity) in hours of reduced solar and wind electricity production, (iv) export electricity to the grid at peak hours - building peak loads usually doesn’t coincide with the grid peak loads and (v) contribute to the demand response strategy while operating with a high EUF, exergy efficiency and ETE.

TABLE 7 - CASES 1 TO 8 RESULTS SUMMARY

		CASE 1 - 400 kW			CASE 2 - 600 kW			CASE 3 - 800 kW		
		LOW EFF	MED EFF	HIGH EFF	LOW EFF	MED EFF	HIGH EFF	LOW EFF	MED EFF	HIGH EFF
1	annual electricity consumption (Kwh/year)	10,771,365.6	10,771,365.6	10,771,365.6	10,771,365.6	10,771,365.6	10,771,365.6	10,771,365.6	10,771,365.6	10,771,365.6
2	annual corrected elect consump. (kWh/year)	9,706,485.7	10,061,264.4	10,238,834.9	9,323,569.0	9,805,920.9	10,047,343.8	9,017,521.9	9,601,666.1	9,894,165.3
3	Net trig electricity production (kWh/year)	3,408,736.1	3,408,736.1	3,408,736.1	5,113,104.0	5,113,104.0	5,113,104.0	6,730,678.3	6,793,133.1	6,805,956.5
4	grid consumption (kWh/year)	6,297,749.6	6,652,528.3	6,830,098.8	4,210,465.0	4,692,816.9	4,934,239.8	2,286,843.6	2,808,533.1	3,088,208.8
5	hot water consumption (kWh/year)	525,258.0	525,258.0	525,258.0	525,258.0	525,258.0	525,258.0	525,258.0	525,258.0	525,258.0
6	hot water production SC (kWh/year)	141,185.7	141,185.7	141,185.7	233,941.9	233,941.9	233,941.9	259,877.9	259,961.9	259,970.0
7	hot water production PC (kWh/year)	99,036.1	99,036.1	99,036.1	251,224.3	251,224.3	251,224.3	265,049.6	264,965.6	264,957.5
8	hot water surplus (kWh/year)	285,036.2	285,036.2	285,036.2	40,091.8	40,091.8	40,091.8	330.4	330.5	330.4
9	average annual EUF (%)	80.96	80.96	80.96	78.40	78.40	78.40	75.30	75.09	75.05
10	average annual Exergy Efficiency (%)	36.70	36.70	36.70	36.67	36.67	36.67	36.76	36.79	36.79
11	average annual engine load (%)	100.00	100.00	100.00	100.00	100.00	100.00	98.72	99.64	99.83
12										
13	electricity production efficiency (%/100)	0.40	0.50	0.60	0.40	0.50	0.60	0.40	0.50	0.60
14	hot water production efficiency (%/100)	0.70	0.80	0.90	0.70	0.80	0.90	0.70	0.80	0.90
15	PEC (kWh/year) =	27,678,782.5	22,199,303.6	18,535,895.9	27,678,782.5	22,199,303.6	18,535,895.9	27,678,782.5	22,199,303.6	18,535,895.9
16										
17	engine fuel (NG) consumption (kWh/year)	8,450,405.3	8,450,405.3	8,450,405.3	12,681,493.1	12,681,493.1	12,681,493.1	16,604,450.0	16,745,718.6	16,774,795.3
18	electricity surplus (kWh/year)	6,297,749.6	6,652,528.3	6,830,098.8	4,210,465.0	4,692,816.9	4,934,239.8	2,286,843.6	2,808,533.1	3,088,208.8
19	hot water surplus (kWh/year)	285,036.2	285,036.2	285,036.2	40,091.8	40,091.8	40,091.8	330.4	330.5	330.4
20	Trigeneration PEC (kWh/year)	24,601,973.9	22,111,757.1	20,150,610.2	23,264,929.6	22,117,241.6	20,949,772.5	22,322,031.1	22,363,197.8	21,922,177.1
21										
22	ETE equivalent thermal efficiency (%)	55.18	50.54	48.16	54.73	50.34	48.07	53.51	49.49	47.45
23	ETE 10% grid loss (%)	61.31	56.15	53.51	60.81	55.93	53.41	59.46	54.99	52.72
24	ETE 20% grid loss (%)	68.98	63.17	60.20	68.41	62.92	60.09	66.89	61.86	59.31
25										
26	average engine elect. efficiency (%)	40.34	40.34	40.34	40.32	40.32	40.32	40.54	40.57	40.57
27	average net electricity production (kWh)	389.13	389.13	389.13	583.69	583.69	583.69	768.34	775.47	776.94
28	(1 - (new cons/ initial cons))*100 (%)	9.89	6.59	4.94	13.44	8.96	6.72	16.28	10.86	8.14

		CASE 4 - 1200 kW - ELECTRICAL DISPATCH			CASE 5 - 1200 kW - FULL LOAD			CASE 6 - 1200 kW - ENGINE LOAD		
		LOW EFF	MED EFF	HIGH EFF	LOW EFF	MED EFF	HIGH EFF	LOW EFF	MED EFF	HIGH EFF
1	annual electricity consumption (Kwh/year)	10,771,365.6	10,771,365.6	10,771,365.6	10,771,365.6	10,771,365.6	10,771,365.6	10,771,365.6	10,771,365.6	10,771,365.6
2	annual corrected elect consump. (kWh/year)	8,773,832.4	9,434,795.6	9,768,825.8	8,766,570.7	9,434,494.1	9,768,797.4	8,777,661.7	9,437,349.1	9,770,740.8
3	Net trig electricity production (kWh/year)	8,330,855.4	8,770,091.4	8,979,531.7	10,226,208.1	10,226,208.1	10,226,208.1	7,329,864.0	7,454,699.6	7,513,308.3
4	grid consumption (kWh/year)	442,976.9	664,704.2	789,294.0	(1,459,637.3)	(791,713.9)	(457,410.6)	1,447,797.8	1,982,649.5	2,257,432.5
5	hot water consumption (kWh/year)	525,258.0	525,258.0	525,258.0	525,258.0	525,258.0	525,258.0	525,258.0	525,258.0	525,258.0
6	hot water production SC (kWh/year)	359,479.2	361,915.9	362,980.8	367,276.2	367,276.2	367,276.2	300,441.1	300,819.9	300,987.7
7	hot water production PC (kWh/year)	161,415.8	162,750.4	162,277.5	157,982.2	157,982.2	157,982.2	189,660.9	193,053.1	193,477.3
8	hot water surplus (kWh/year)	4,363.0	591.7	(0.3)	(0.4)	(0.4)	(0.4)	35,156.0	31,385.1	30,793.0
9	average annual EUF (%)	73.46	72.30	71.77	69.44	69.44	69.44	76.52	76.25	76.10
10	average annual Exergy Efficiency (%)	37.31	37.51	37.60	38.14	38.14	38.14	36.83	36.88	36.90
11	average annual engine load (%)	81.46	85.75	87.80	100.00	100.00	100.00	71.70	72.93	73.50
12										
13	electricity production efficiency (%/100)	0.40	0.50	0.60	0.40	0.50	0.60	0.40	0.50	0.60
14	hot water production efficiency (%/100)	0.70	0.80	0.90	0.70	0.80	0.90	0.70	0.80	0.90
15	PEC (kWh/year) =	27,678,782.5	22,199,303.6	18,535,895.9	27,678,782.5	22,199,303.6	18,535,895.9	27,678,782.5	22,199,303.6	18,535,895.9
16										
17	engine fuel (NG) consumption (kWh/year)	20,128,631.6	21,067,049.1	21,512,033.5	24,145,511.5	24,145,511.5	24,145,511.5	17,984,552.8	18,248,486.2	18,371,706.4
18	electricity surplus (kWh/year)	442,976.9	664,704.2	789,294.0	(1,459,637.3)	(791,713.9)	(457,410.6)	1,447,797.8	1,982,649.5	2,257,432.5
19	hot water surplus (kWh/year)	4,363.0	591.7	(0.3)	(0.4)	(0.4)	(0.4)	35,156.0	31,385.1	30,793.0
20	Trigeneration PEC (kWh/year)	21,242,306.8	22,397,197.1	22,827,523.1	20,496,417.6	22,562,083.1	23,383,160.0	21,654,270.1	22,253,016.5	22,168,308.4
21										
22	ETE equivalent thermal efficiency (%)	53.28	49.52	47.70	52.28	49.23	47.66	53.94	49.85	47.77
23	ETE 10% grid loss (%)	59.20	55.02	53.00	58.09	54.70	52.95	59.94	55.39	53.08
24	ETE 20% grid loss (%)	66.60	61.89	59.62	65.35	61.53	59.57	67.43	62.31	59.71
25										
26	average engine elect. efficiency (%)	41.39	41.63	41.74	42.35	42.35	42.35	40.76	40.85	40.90
27	average net electricity production (kWh)	951.01	1,001.15	1,025.06	1,167.38	1,167.38	1,167.38	836.74	850.99	857.68
28	(1 - (new cons/ initial cons))*100 (%)	18.54	12.41	9.31	18.61	12.41	9.31	18.51	12.38	9.29

		CASE 7 - 1560 kW - ELECTRICAL DISPATCH			CASE 8 - 1560 kW - FULL LOAD		
		LOW EFF	MED EFF	HIGH EFF	LOW EFF	MED EFF	HIGH EFF
1	annual electricity consumption (Kwh/year)	10,771,365.6	10,771,365.6	10,771,365.6	10,771,365.6	10,771,365.6	10,771,365.6
2	annual corrected elect consump. (kWh/year)	8,755,596.6	9,427,176.1	9,763,309.5	8,755,596.6	9,427,176.1	9,763,309.5
3	Net trig electricity production (kWh/year)	8,808,417.4	9,387,434.0	9,677,973.7	13,294,070.7	13,294,070.7	13,294,070.7
4	grid consumption (kWh/year)	(52,820.8)	39,742.1	85,335.8	(4,538,474.1)	(3,866,894.6)	(3,530,761.1)
5	hot water consumption (kWh/year)	525,258.0	525,258.0	525,258.0	525,258.0	525,258.0	525,258.0
6	hot water production SC (kWh/year)	367,126.2	372,591.1	374,958.1	389,437.1	389,437.1	389,437.1
7	hot water production PC (kWh/year)	157,652.0	152,667.1	150,299.7	135,821.3	135,821.3	135,821.3
8	hot water surplus (kWh/year)	479.8	(0.2)	0.1	(0.3)	(0.3)	(0.3)
9	average annual EUF (%)	69.78	68.41	67.73	62.59	62.59	62.59
10	average annual Exergy Efficiency (%)	35.98	36.21	36.33	37.51	37.51	37.51
11	average annual engine load (%)	66.26	70.61	72.79	100.00	100.00	100.00
12							
13	electricity production efficiency (%/100)	0.40	0.50	0.60	0.40	0.50	0.60
14	hot water production efficiency (%/100)	0.70	0.80	0.90	0.70	0.80	0.90
15	PEC (kWh/year) =	27,678,782.5	22,199,303.6	18,535,895.9	27,678,782.5	22,199,303.6	18,535,895.9
16							
17	engine fuel (NG) consumption (kWh/year)	21,992,215.2	23,251,905.9	23,883,396.5	31,741,247.1	31,741,247.1	31,741,247.1
18	electricity surplus (kWh/year)	(52,820.8)	39,742.1	85,335.8	(4,538,474.1)	(3,866,894.6)	(3,530,761.1)
19	hot water surplus (kWh/year)	479.8	(0.2)	(0.3)	(0.3)	(0.3)	(0.3)
20	Trigeneration PEC (kWh/year)	21,860,848.7	23,331,389.8	24,025,622.5	20,395,061.5	24,007,457.6	25,856,644.9
21							
22	ETE equivalent thermal efficiency (%)	50.96	47.49	45.86	49.40	47.09	45.90
23	ETE 10% grid loss (%)	56.62	52.77	50.96	54.89	52.32	51.00
24	ETE 20% grid loss (%)	63.69	59.37	57.33	61.75	58.86	57.38
25							
26	average engine elect. efficiency (%)	40.05	40.37	40.52	41.88	41.88	41.88
27	average net electricity production (kWh)	1,005.53	1,071.62	1,104.79	1,517.59	1,517.59	1,517.59
28	(1 - (new cons/ initial cons))*100 (%)	18.71	12.48	9.36	18.71	12.48	9.36

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NOMENCLATURE

COP – coefficient of performance (-)
E_c – energy consumption (kWh)
E_{hw} – hot water energy consumption (kWh)
E_{cw} – chilled water energy consumption (kWh)
E_{hws} – surplus hot water energy consumption (kWh)
E_{hwT} – trigeneration hot water energy production (kWh)
E_{st} – steam energy consumption (kWh)
E_{sts} – surplus steam energy consumption (kWh)
E_{stT} – trigeneration steam energy production (kWh)
E_{elet} – electricity consumption (kWh)
E_{eletav} – avoided electricity consumption (kWh)
E_{eletT} – trigeneration electricity production (kWh)
E_{cwT} – trigeneration chilled water production (kWh)
PEC – primary energy consumption (kWh)
$PEC_{without}$ – PEC without a cog/trig system (kWh)
$PEC_{withTrig}$ – PEC with a cog/trig system (kWh)

η_{hw} – hot water production efficiency

η_{hws} – surplus hot water production efficiency

η_{st} – steam production efficiency

η_{sts} – surplus steam production efficiency

η_{elet} – electricity production efficiency

ETE – equivalent thermal efficiency

ETE_{GL} – equivalent thermal efficiency with grid loss

E_{trig} – trigeneration energy consumption (kWh)

$F_{gridloss}$ – grid loss electricity factor (-)

EUF – energy utilization factor (-)

W_{net} – net electricity production (kW)

LHV – fuel lower heating value (kW)

m – mass flow (kg/s)

m_{fuel} – fuel mass flow (kg/s)

h – enthalpy (kJ/kg)

s – entropy (kJ/kg.K)

ech_{fuel} – fuel chemical exergy (kW)

Ex – exergy flow (kW)

To – reference temperature (K)

ε – exergy efficiency