SIMULATION OF AN INTERNAL COMBUSTION ENGINE COGENERATION SYSTEM: ONE ENGINE OF 590 kWe WITH HRSG, ECONOMIZER AND HEAT EXCHANGERS

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Abstract. *Cogeneration systems have been proposed for sites of coincident electrical and thermal loads as an energy saving alternative. Site electrical and thermal loads demands can vary in a large range that makes cogeneration systems achieve high energy utilization factor (EUF) at hours of coincident high demands and low EUF at hours of low coincident demands. The energy balance of the prime mover can be compared with the energy demands turning possible to evaluate different options and predict the performance of the cogeneration system. Simulation of thermal systems is a tool to well design power plants, helping designers evaluate possibilities trying to turn the system economically and technically feasible. In this work a computational hourly profile simulation methodology that combines curve fittings from literature and manufactures data, mathematical representations of physical phenomena's and properties and system design parameters are used to predict the performance of an engine cogeneration system configuration. The system is sized to turn the site independent of the electricity from the grid. Three cases are evaluated and compared revealing different energy utilization factor and primary energy savings.*

Keywords: *cogeneration, integrated thermal system, engine, software, computational simulation, iterative procedures.*

1. INTRODUCTION

High efficiency thermal plants contribute to reduce environmental impacts of fossil fuel combustion as they substitute lower efficiency older thermal plants and contribute with a more sustainable growth of the electrical system.

Thermal plants efficiencies are being raised by advances in engineering technologies fields such as materials, fluid flow, heat transfer, combustion, and others. Cogeneration systems take advantages of these advances (incorporated at the equipment), but a site energy demand analysis and the simulation of the system plays an important role in the final primary energy savings.

Computational thermodynamics should be used for the purpose, since the evaluation of cogeneration systems involves several variables and calculations. Energy balances, load profiles, equipment performance, operational strategies, legislation aspects, operational costs, investments, environmental aspects, taxes, etc are some of the fields that must be dealt with.

Cogeneration systems design can conduct to systems that doesn't meet all energy demands of the site, auxiliary equipments must meet particular loads and complementary equipments must meet peak loads (i.e. electricity: grid). Cogeneration system can be sized to attend the base of the electricity demand to the exportation of electricity to the grid. Cogeneration systems design permits several sizes for the prime mover and many system conceptions.

2. CASE STUDY: HOSPITAL

In this case study, a typical load of a local hospital is assessed. The profiles were previously utilized at others works (Espirito Santo 2005, 2006, 2006a and 2007) and they will be now used again in order to establish a comparison between the case studies.

The profiles weren't measured but through the analysis of electricity and gas bills and the installed equipments (chillers, boilers, water heaters, etc), it was possible to construct expected profiles for the main energy demands in the hospital.

Figure 1 shows a typical electricity demand profile. The figure was constructed with data of consumption at peak and out of peak hours, during the whole year of 2003. Figure 2 shows a typical demand profile of hot water for sanitary purpose (50^o C) and saturated steam demand at 7 bar. It was estimated based on the existing equipment and the gas bill. Figure 3 shows the cooling load (air conditioning) profile, based on characteristics of existing equipment, activity of the hospital and typical cooling load profiles for summer at the hospital location. At figure 4 a typical summer weather profile (dry bulb temperature and relative humidity) can be seen.

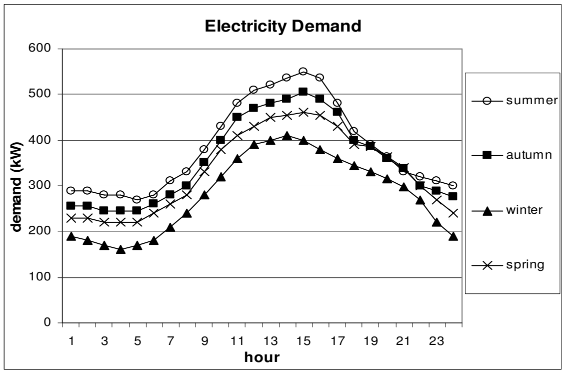

Figure 1 – Electricity demand

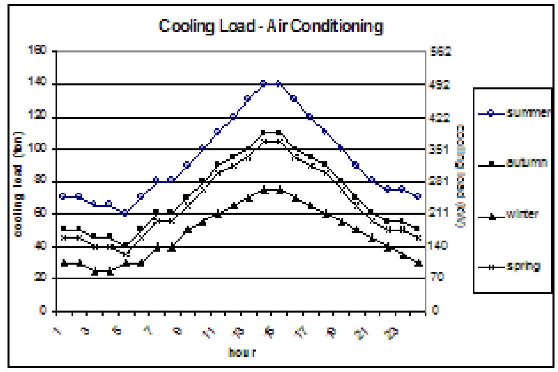

Figure 3 – Cooling load

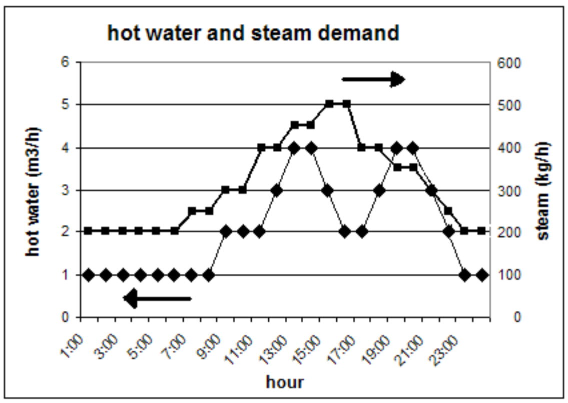

Figure 2 – Hot water and steam demand

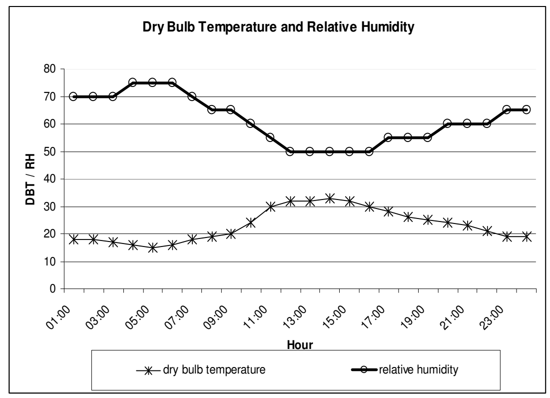

Figure 4 – local weather profile

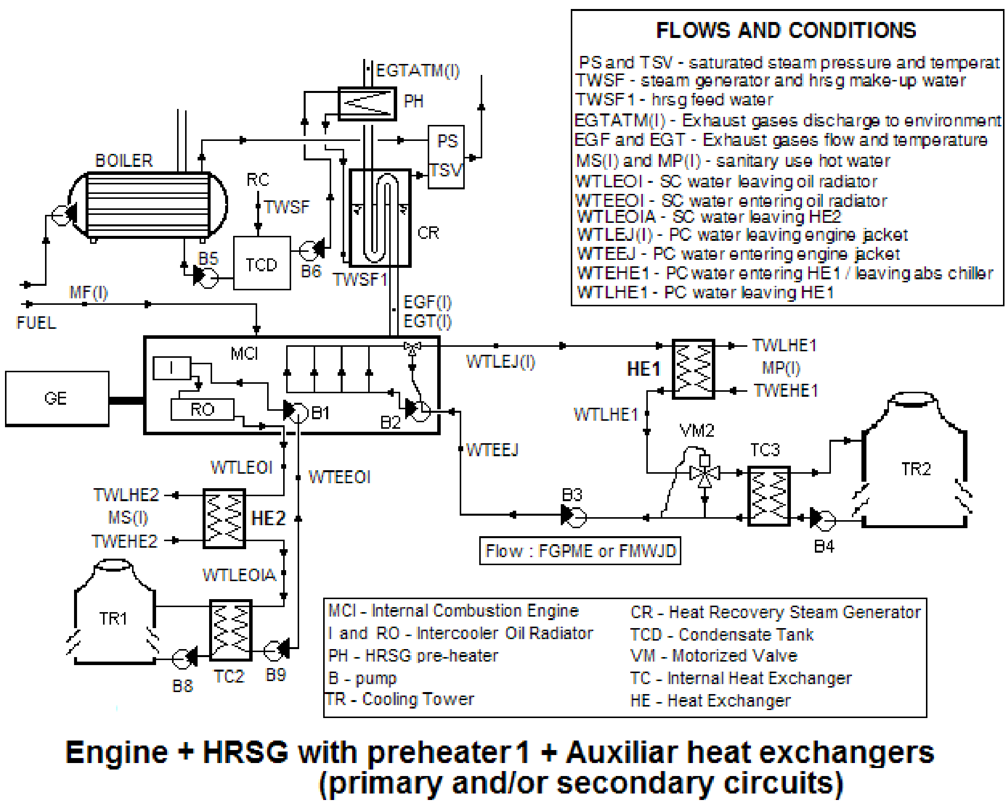

Figure 5 – Cogeneration Scheme

3. METHODOLOGY

The results presented here were obtained through a software that is being developed by the author consisting of Fortran engineering programs and a Delphi interface. Graphical results are directly generated by a spreadsheet file (Excel) that imports data from result files. The Fortran program is composed of one main algorithm and more than 20 subroutines, including i) five different engines, ii) water and steam properties, iii) exhaust gas properties, iv) absorption chiller selection, v) absorption chiller simulation, vi) heat recovery steam generator (HRSG) simulation, vii) economizer design, viii) economizer simulation, ix) exhaust gas heat exchanger design, x) exhaust gas heat exchanger simulation, among others.

The main program controls data entry, results and all calculation procedures. Calculation procedures use curve fitting of polynomial expressions (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). A computational algorithm involving several iterative procedures was developed, constituting an integrated thermal system that considers all equipment as operating as a single system. It produces results as a function of demands, energy supplied by engine, design parameters, equipment performance, etc. A thermal system integration overview can be seen in Smith (2005).

The hourly profile analysis simulation applied here 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-steps, as used by Lebrun (1999). Some computational routines developed in previous papers were used in this project, including: gas turbines cogeneration (Espirito Santo and Gallo 1999 and 2000), combined cycle (Espirito Santo and Gallo 2001), and combined cycle optimization (Espirito Santo 2003).

4. COGENERATION CONCEPTION

Figure 5 shows the cogeneration configuration that will be evaluated here. It is formed by one internal combustion engine, primary and secondary circuits, heat recovery steam generator (HRSG), HRSG economizer and auxiliary equipments (pumps, cooling towers, heat exchangers).

Energy from the engine exhaust gases are used for steam generation in a HRSG with economizer. Primary circuit recovers energy from the engine jacket. The energy of the primary circuit is used to warm water for sanitary purpose (after recovery at secondary circuit). Secondary circuit recovery energy from the oil radiator of the engine and utilize it to warm water for sanitary purpose.

Figure 6 reveals the energy balance of the proposed engine as a function of engine load and figure 7 reveals the exhaust gases flow and temperature as a function of engine load. Maximum engine thermal efficiency is found at load near 0.8 (36.5%). Corrections for atmospheric pressure and dry bulb temperature are considered, but in this study only dry bulb corrections are applied considering a 0.5% loss of power for each degree centigrade above 25^{o}C. The engine has an electric output power of 590 kWe at full load. Engine energy balance is based on ASHRAE 2000.

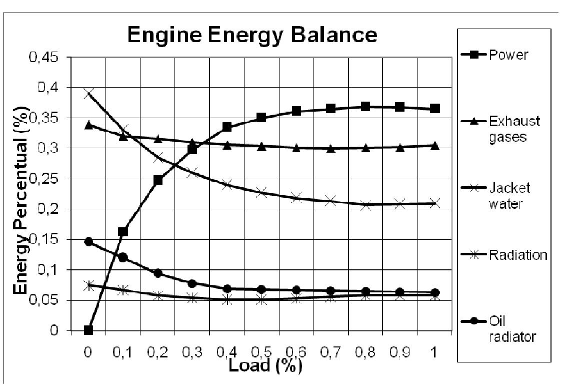

Figure 6 – Engine Energy Balance

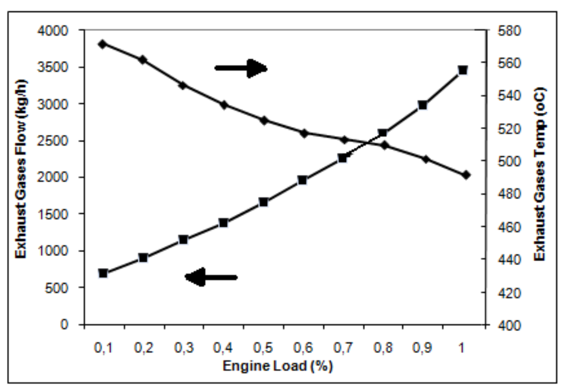

Figure 7 – Exhaust Gases Flow and Temperature

5. DESIGN PARAMETERS

Three different cases will be compared, as described below:

Case 1: one engine of 590 kWe operating at electrical dispatch, primary and secondary circuits with recovery heat exchangers HE1 and HE2 for sanitary use hot water production, and exhaust gases energy used for steam generation at a heat recovery steam generator (HRSG).

Case 2: the same engine of case 1 operating at electrical dispatch, primary and secondary circuits with recovery heat exchangers HE1 and HE2 for sanitary use hot water production and exhaust gases flow passing through a heat recovery steam generator (HRSG) with economizer.

Case 3: the same scheme of case 1 operating at full load, primary and secondary circuits with recovery heat exchangers HE1 and HE2 for sanitary use hot water production and exhaust gases flow energy used for steam generation at a heat recovery steam generator with economizer.

Water flows at primary and secondary circuit are designed taking into account the engine energy at the circuit and the design temperature difference.

At design condition secondary circuit water enter the engine at 35°C and leave the engine at 50°C. Heat exchanger HE2 utilized to recover energy from the secondary circuit (hot water for sanitary purpose) was designed to reach an approach point of 1.7°C with the engine at full load.

At design condition (engine full load) the primary circuit hot water should enter the engine (jacket) at 70°C and leave it at 90°C. After leaving the engine hot water enters HE1 (heat exchanger to warm sanitary use water). Heat exchanger HE1 utilized to reheat the hot water for sanitary purpose was designed to reach an approach point of 5,6°C with the engine at full load.

Heat recovery steam generator was designed to produce saturated steam at 7 bar (700 kPa). HRSG physical characteristics are: 150 tubes with diameter of 25.4 / 37.8 mm (internal/external) and 4 meter long. Heat loss of 2% and blow down of 2% were also adopted. Heat recovery steam generator feed water economizer was designed to achieve an approach point of 12°C and a heat loss of 2%. Exhaust gas properties (specific heat, viscosity and thermal conductivity) is evaluated at the mean temperature in the HRSG and in the economizer. Exhaust gas composition is maintained fixed independent of the engine load. The simulation of the HRSG and the HRSG economizer is developed accordingly with the methodology proposed by Ganapathy (1991).

Cooling towers and auxiliary heat exchangers are responsible to reject energy not utilized, preventing engine to operate under unsafe condition. Design of these equipments will not be simulated here, it is assumed that they can reject the energy as needed.

Total electricity produced is 3% higher then net engine power, taking into account the use of electricity in auxiliary equipment. No heat loss is assumed at hot water pipes and exhaust gas ducts.

5. TECHNICAL RESULTS

5.1 Electricity

Figure 8 shows the electricity demand, the total engine power and the net available power. As mentioned, cases 1 and 2 operate at electrical dispatch and the electricity generation curves are coincident. Since the engine met the hospital electricity demand at the peak hours there is no electricity being changed with the grid. At case 3 the engine operates at full load and the excess of electricity must be transferred to the grid.

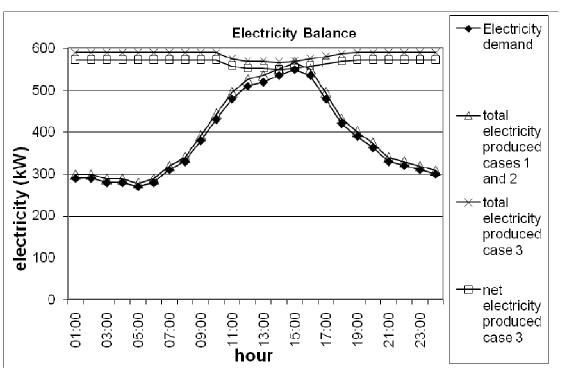

Fig. 8 – electricity demand/generation (cases 1, 2 and 3)

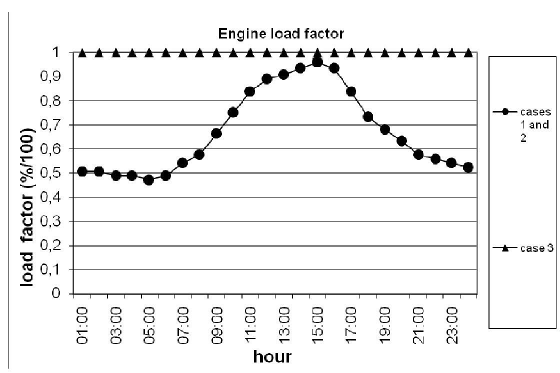

Fig. 9 – engine load factor (cases 1, 2 and 3)

The total engine power is 3% higher then demand due to auxiliary equipments of the cogeneration plant.

Figure 9 shows the engine load factor operating at the two defined condition (electrical dispatch and full load). When the engine is operating at full load, the power remains near 590 kWe all the time, with small decreases between hours 11 and 17 due to high ambient dry bulb temperature.

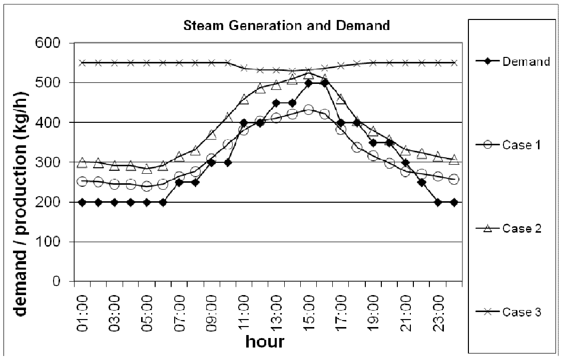

Fig. 10 – steam demand / generation (cases 1, 2 and 3)

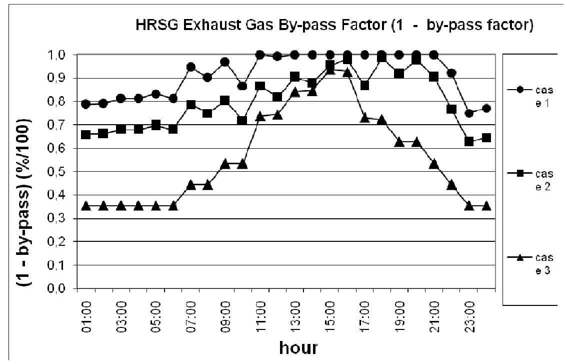

Fig. 11 – exhaust gases by-pass (cases 1, 2 and 3)

5.2 Steam Generation

Figure 10 shows the steam balance obtained through the system simulation. Evaluating case 1 we can see that the steam demand can be attended by the cogeneration system during the hours 1 to 10, 12 and 22 to 24, at the remaining hours the existing steam generator must produce the complementary amount.

At case 2 due to the existence of the economizer a higher quantity of steam can be produced by the cogeneration system. It can be noted that all the hospital demand is reached by the cogeneration system.

Evaluating case 3 we can note that the steam demand is also completely reached by the cogeneration system.

Figure 11 shows the exhaust gas by passing the HRSG and economizer to avoid the steam production that is not being demanded by the hospital.

Figures 12 and 13 show the engine exhaust gas flow and temperature. A reduction on the engine gas flow and a raise in the exhaust gas temperature can be noted when the engine operates at part load.

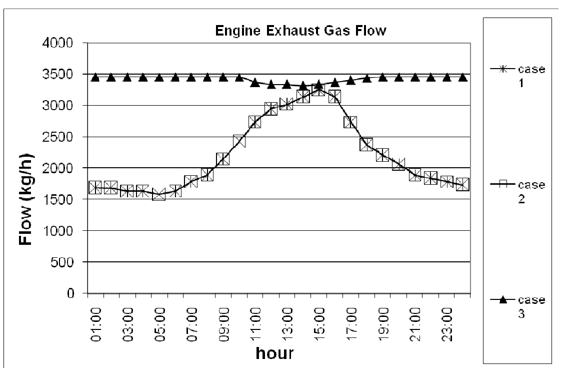

Fig. 12 – Engine exhaust gas flow (cases 1, 2 and 3)

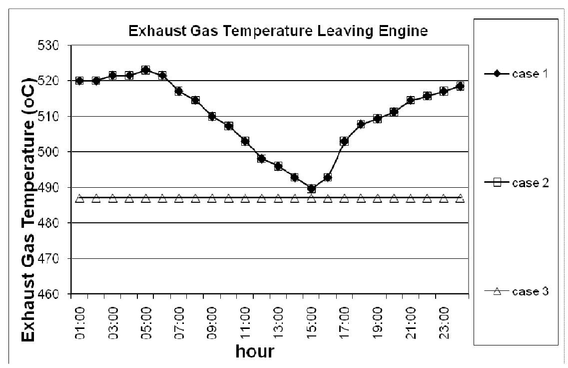

Fig 13 – Engine exhaust gas temperature (cases 1 to 3)

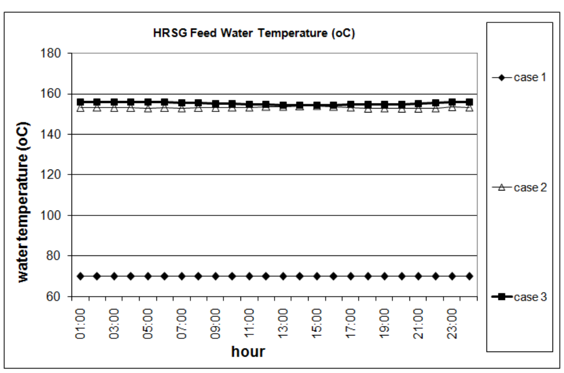

Fig. 14 – HRSG feed water temperature (cases 1 to 3)

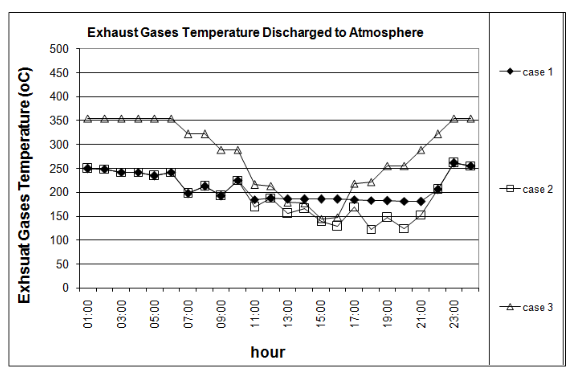

Fig 15 – Exhaust gas temperature discharged to atmosphere (cases 1, 2 and 3)

Figure 14 shows the HRSG feed water temperature. At case 1 the water enters the HRSG at 70^{o}C since there is no economizer. At cases 2 and 3 the water entering the HRSG is warmed until the economizer approach point previously defined (12^{o}C - design criteria for HRSG economizer). The exhaust gases temperature being discharged to the atmosphere can be seen in figure 15, these results considers the mixture of the gases that passes through the HRSG and the portion that is by-passed.

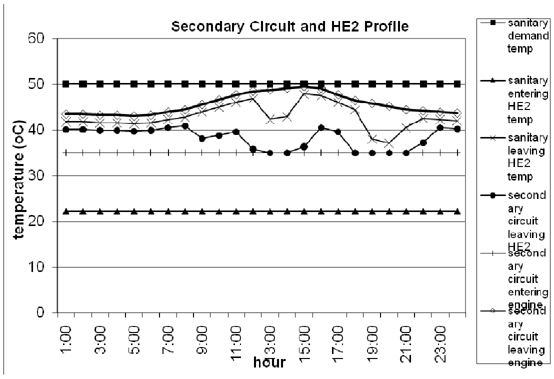

Fig 16 – Secondary circuit balance (cases 1 and 2)

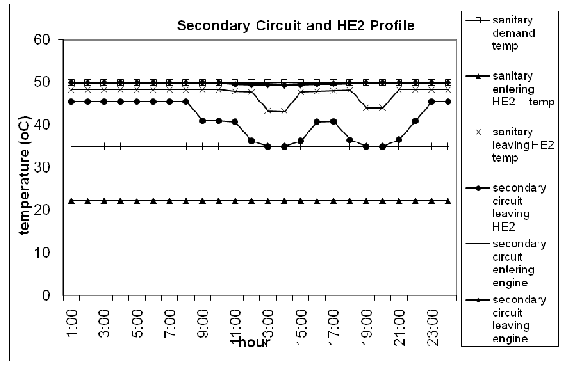

Fig 17 – Secondary circuit balance (case 3)

5.3 Engine Secondary Circuit (SC)

Energy balance at secondary circuit can be checked at figures 16 and 17. Secondary circuit water enters the engine at 35^{o} C (fixed) and leave the engine at 50^{o} C with engine at full load. Considering the engine at part load the temperature depends on engine load and oil radiator energy percentage. Secondary circuit water temperature leaving HE2 reveals the amount of recovered energy.

At figure 16 the results obtained with case 1 and 2 can be checked. Engine secondary circuit hot water temperature leaves the engine between 43^{o}C (hour 5) and 49.5^{o}C (hour 15). Sanitary use hot water enters HE2 at 22.2^{o}C (fixed) and leaves it between 37^{o}C (hour 20) and 47.8^{o}C (hour 15), depending on energy available, sanitary use hot water demand (figure 2) and the approach point at HE2. It can be seen that energy is being rejected at hours 1 to 12, 15 to 17 and 22 to 24. Heat exchanged at HE2 is between 22 kW and 96 kW.

Case 3 secondary circuit energy balance can be checked at figure 17. Secondary circuit hot water leaves the engine at 50^{o}C during all the day, since the engine operates at full load all the time. Sanitary use hot water is warmed between 43.2^{o}C (hour 14) and 48.3^{o}C (hour 1). Energy is rejected at hours 1 to 12, 15 to 18 and 21 to 24. Heat exchanged at HE2 is between 30 kW and 101 kW.

5.4 Engine Primary Circuit (PC)

Figures 18 and 19 show the primary circuit energy balance for cases 1 to 3. The results obtained for cases 1 and 2 are demonstrated at figure 18. Sanitary use hot water enters HE1 at the same temperature it leaves HE2 (figure 16). Sanitary use hot water is warmed to the design condition (50^{o}C) at all day hours. A small recovery of primary circuit energy can be checked, since the primary circuit water temperature leaving engine and leaving HE1 is almost coincident, a temperature difference can be seen at hours 13, 14 and 19 to 21. Heat exchanged at HE1 is between 6 kW and 35 kW.

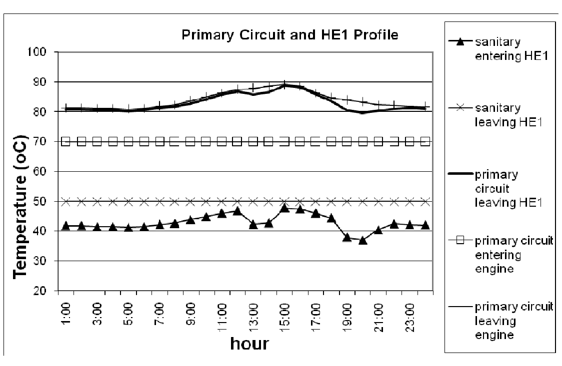

Fig 18 – Primary circuit balance (Cases 1 and 2)

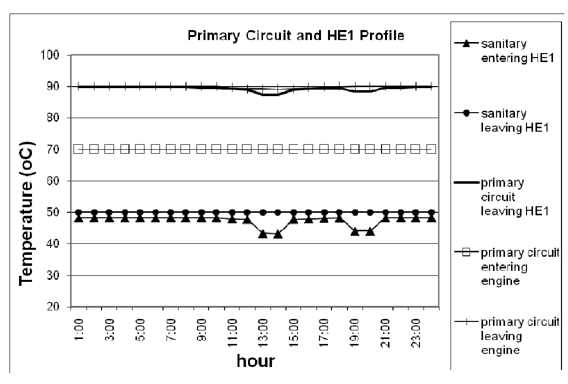

Fig 19 - Primary circuit balance (Case 3)

At case 3 (figure 19) sanitary use hot water also enters HE1 at the temperature it leaves HE2 (figure 17). Sanitary use hot water is also warmed to the design condition (50^{o}C) at all day hours. A small energy recovered can be checked. Heat exchanged at HE1 is between 2 kW and 31.5 kW.

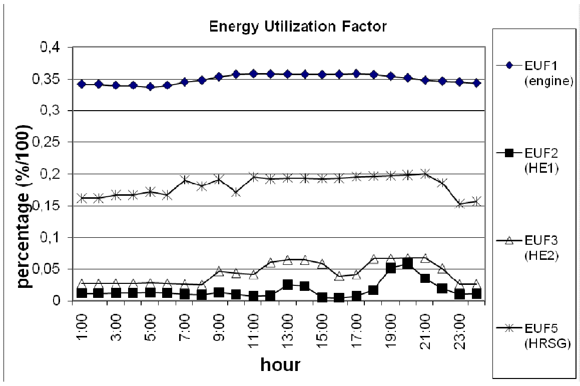

Figure 20 – Energy Utilization Factor (Case 1)

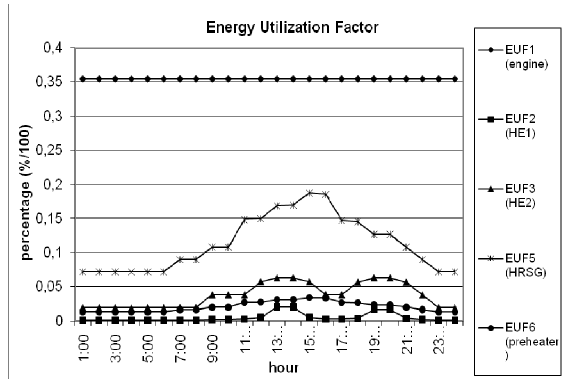

Figure 22 – Energy Utilization Factor (Case 3)

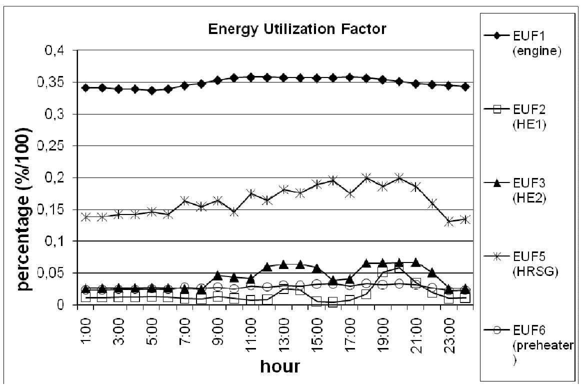

Figure 21 – Energy Utilization Factor (Case 2)

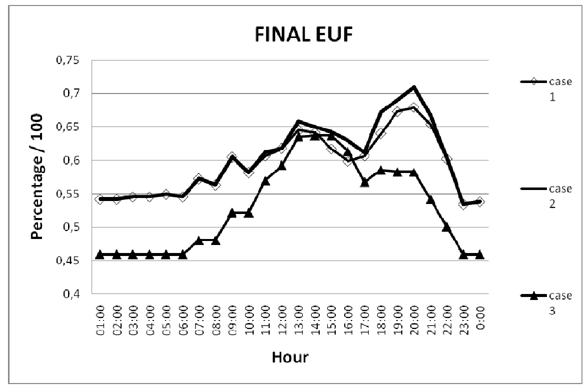

Figure 23 – Final Energy Utilization Factor

5.5 Energy Utilization Factor

The Energy Utilization Factor is calculated as the percentage of energy recovered from the engine to meet a particular energy demand. The contribution to EUF of case 1 is seen in Figure 20. Since the engine operates following the electricity demand, engine thermal efficiency (electricity generation) varies between 34 and 36%. Between 0.4 and 5.8% of the engine energy is recovered at heat exchanger HE1 while between 2.5% and 6.7% is recovered at HE2. At the HRSG between 15.3 and 20.4% of the engine energy consumption is recovered.

The contribution to EUF of case 2 is shown at Figure 21. Since the engine operates at the same condition of case 1, engine thermal efficiency (electricity generation) and the energy recovered at heat exchangers HE1 and HE2 have the same EUF results. At the HRSG between 13 and 19.9% of the engine energy is recovered, and close to 3% is recovered at the HRSG economizer.

The contribution to EUF of case 3 is seen in Figure 22. Since the engine operates at full load an almost constant engine thermal efficiency (electricity generation) equal to 36% is shown. Between 0.1% and 2% of the engine energy is recovered at heat exchanger HE1 while between 2 and 6% of the engine energy is recovered at HE2. At the HRSG between 7 and 18.5% of the engine energy is recovered, and between 1.3 and 3.3% is recovered at HRSG economizer.

The sum of the partial values for cases 1 to 3 can be seen at figure 23. A mean value of 59.3%, 60.1% and 53% is obtained for cases 1, 2 and 3 respectively.

6. ENERGY DAILY ANALYSIS

As the energy demands is not attended by the proposed cogeneration system (different energy profiles that the ones considered at this work), supplementary energy must be used to warm sanitary use hot water to the design condition (50°C) at an auxiliary boiler, additional steam should be produced at a steam generator and additional electricity should be bought from the grid.

Table 1 shows a daily kWh energy analysis for the hospital. Electricity, hot water and steam consumption reach 15907.6 kWh per day (column 1 of Table 1) if conversion factors (efficiency) are not taken into account. Assuming efficiencies of 30% for electricity production and 80% for steam generation and hot water production, the energy daily consumption raises to 39015.75 kWh (second column of Table 1). Assuming efficiencies of 38% for electricity production and 80% for steam generation and hot water production, the energy daily analysis raises to 32571.54 kWh (third column of table 1).

Table 2 shows the daily energy analysis of the proposed cogeneration schemes. Cases 1 and 2 schemes produce 9468.5 kWh/day of electricity while case 3 produce 14032 kWh/day. Deducting the parasitic electricity of the cogeneration system (3%), the net electricity production is 9183 kWh/day for cases 1 and 2 and 13611 kWh/day for case 3 (line 1). A natural gas consumption of 26140 kWh/day (line 2) was calculated for cases 1 and 2 and equal to 38733 kWh/day for case 3. All cases don't need additional energy to warm sanitary use hot water. In order to meet the steam demand, case 1 needs 358.5 kWh/day (line 5 of table 2) while cases 2 and 3 don't need additional energy to produce additional steam.

Line 3 shows the electricity to be exported to the grid. In Table 2, numbers in parentheses do not take into account the conversion efficiencies, whereas numbers in brackets do. Case 3 exports 4428 kWh/day of electricity to the grid. Considering an electric system with 30% of thermal efficiency a primary energy savings equal to 14760 kWh/day is predicted. Considering an electric system with 38% of thermal efficiency a primary energy savings equal to 11653 kWh/day is calculated.

Final results are in the last line of Table 2. Comparing the actual demand of energy considering an electrical system with a mean thermal efficiency of 30% (39015.75 kWh) shown in table 1 and the energy demand with cases 1 (26498.5 kWh/day), case 2 (26140 kWh/day) and case 3 (23973 kWh/day) cogeneration systems (Table 2), primary energy consumption reductions of 32.1%, 33% and 39% were obtained, respectively. Considering a electrical system with a mean thermal efficiency of 38%, the primary energy consumption of case 3 need to be recalculated since the surplus electricity avoid primary energy consumption of thermal plants with 38% of thermal efficiencies (line 4 of table 2). Primary energy reductions of 18.6%, 19.7% and 16.9% were obtained, respectively. The results are particular to the defined cogeneration scheme, the design conditions and the energy load profiles (Figures 1 to 4).

Table 1 – Daily Energy Consumption

	actual consume (kWh) no conversion	actual consume (kWh) with conversion (30%)	actual consume (kWh) with conversion (38%)
1 electricity demand (kWh)	9183,00	30610,00	24165,79
2 hot water demand (kWh)	1615,30	2019,13	2019,13
3 steam demand (kWh)	5109,30	6386,63	6386,63
4 total energy consumption (kWh)	15907,60	39015,75	32571,54

Table 2 – Daily Energy Analysis

		case 1 consume (kWh) (no conversion) / [with conversion]	**case 2** consume (kWh) (no conversion) / [with conversion]	**case 3** consume (kWh) (no conversion) / [with conversion]
1	net electricity produced (kWh)	9183	9183	13611
2	cogeneration natural gas (kWh)	26140	26140	38733
3	exported electricity (kWh)	0	0	(-4428) / [-14760 / -11653]
4	complementar hot water (kWh)	0	0	0
5	complementar steam (kWh)	(286.8) / [358.5]	0	0
6	total energy consumption (kWh)	[26498.5]	[26140]	[23973 / 27080]

7. CONCLUSIONS

Considering the EUF as the decision criteria case 2 should be choose since it represents the higher value obtained at the case studies (a mean EUF equal to 60.3% was achieved).

The use of an economizer can increase the EUF up to 3%. A mean increase of 0.8% in the EUF was obtained when introducing the economizer in the HRSG (case 2), since a fraction of the exhaust gases is by-passed during all day hours. Operating the engine at full load a drop in the EUF to 53% was shown, since more engine energy is rejected due to the low energy demands of the hospital if compared with the engine energy balance.

Considering the primary energy savings as the decision criteria two scenarios can be evaluated: i) if the electric system has a mean thermal efficiency lower then the engine thermal efficiency is preferable to operate the engine at full load and then case 3 should be chosen, ii) if the electrical system has a mean thermal efficiency higher then the engine thermal efficiency is preferable to operate the engine following the electricity load (electrical dispatch) and then case 2 should be chosen. This conclusion is valid only if the cogeneration system meets all the hot water and the steam demand of a site, considering the operation either at the electrical dispatch mode or at the full load mode.

The primary energy savings analysis demonstrated that cogeneration system can contribute to raise the mean efficiency of the thermal plants, if a reasonable amount of energy from the exhaust gases and from the primary in secondary circuit is recovered replacing energy consumption in boilers and steam generators.

If electricity transmission loss is taken into account, cogeneration systems can be even more attractive.

For best results, the final decision should take into account initial investment, maintenance, energy load variations throughout the year, electricity contract rules, taxes, operational costs, and other factors mentioned in Hu (1985) and Orlando (1996).

Evaluating the results it can be noted that only a part of the engine primary circuit energy is being recovered. Since there is an air conditioning load in the hospital that actually is attended by electrical chillers, the author suggest the use of this energy to produce chilled water at an absorption chiller as a manner to raise the EUF and the primary energy savings of the proposed cogeneration system. Considering the configuration here evaluated, the elimination of the recovery of energy from the secondary circuit (HE2) can make the system simpler and still warm the sanitary use water to the design condition recovering energy only from the primary circuit (HE1).

A second law analysis and an economic analysis will be developed in future works.

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