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ANNUAL PERFORMANCE ANALYSIS OF ENGINE CHP SYSTEMS AT A TROPICAL CLIMATE HOSPITAL –

REDUCING 19% CO_2 EMISSION WHEN COMPARED TO A HIGH EFFICIENCY SCENARIO – EFFICIENCY, RELIABILITY, RESILIENCE, GRID STABILITY, AND DEMAND RESPONSE

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Introduction

In this Case Study, the COGMCI Software team discusses (i) the best size of an engine CHP system for a tropical climate hospital and improve the discussion about (ii) what the efficiency indicators tell us about the system performance? Which performance indicator should be used when looking to reduce the CO_2 emission?

The COGMCI software is used to simulate and predict the performance of eight different engine CHP case studies for a Hospital located in Campinas – SP - Brazil. An 8760 hours analysis is performed. The building energy demand is predicted through a data acquisition system.

Engine CHP can be an important technology in the migration from fossil fuels to renewables. Every site with coincident electrical and thermal demands is a CHP candidate and has an annual energy savings opportunity (CHP potential). COGMCI can help you size and define the better configuration no matter what your main goal is (i) payback, (ii) grid independence, (iii) CO_2 emissions reduction, or (iv) a combination of them.

This study reveals that engine CHP can save close to 25% primary energy when using the harmonized reference conversion efficiency defined at the EU 2015/2402 directive and close to 19% when using the PES analysis directed obtained by an energy balance approach. These PES are calculated using a high-efficiency scenario (power production, boilers, and electrical chillers) that normally is not the reality of site existing equipment and countries average thermal efficiency.

The Hospital

The hospital is a university hospital located inside the State University of Campinas (Unicamp) campus (figure 1). The hospital is a multi-floor building with a total of 56,000 m^2. The hospital started its activities in 1985 – Unicamp Clinic Hospital (HC Unicamp).

HC Unicamp buys electricity from the electrical grid at a high voltage.

Air conditioning is provided by several individual equipment and some centralized systems. The main centralized system is formed by two screw compressor chiller of 300 RT each and several air handlers (fancoils).

Hot water is provided by combustion heaters using LPG (liquified petroleum gas).

The hospital centralized steam generators provide the steam for the laundry, kitchen, and the sterilization sector.

The hospital building operates 8760 hours per year, but a higher activity occurs at the commercial hours.

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Figure 1 – UNICAMP PUBLIC HOSPITAL

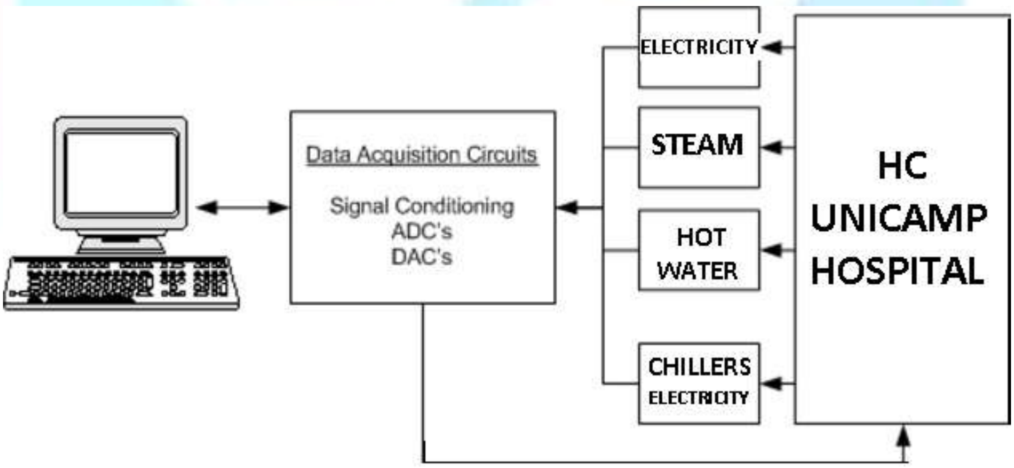

Figure 2 – DATA ACQUISITION SYSTEM

Figure 2 shows the basic architecture of the data acquisition system installed at the hospital. It monitors electricity, steam, hot water, and chillers electrical consumption at a one hour interval.

Local dry bulb temperature and relative humidity were measured by the campus weather station.

Figure 3 shows the dry bulb temperature annual profile and figure 4 reveals the annual relative humidity profile.

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Figure 5 reveals the annual building HVAC cooling load – the main centralized chilled water plant. HC Unicamp electrical power consumption is converted to cooling load assuming an electrical chiller COP. A COP equal to 4.2 (0.8 kW/RT) is utilized to account for the water cooled screw compressor chillers performance. A peak cooling load close to 380 RT is revealed.

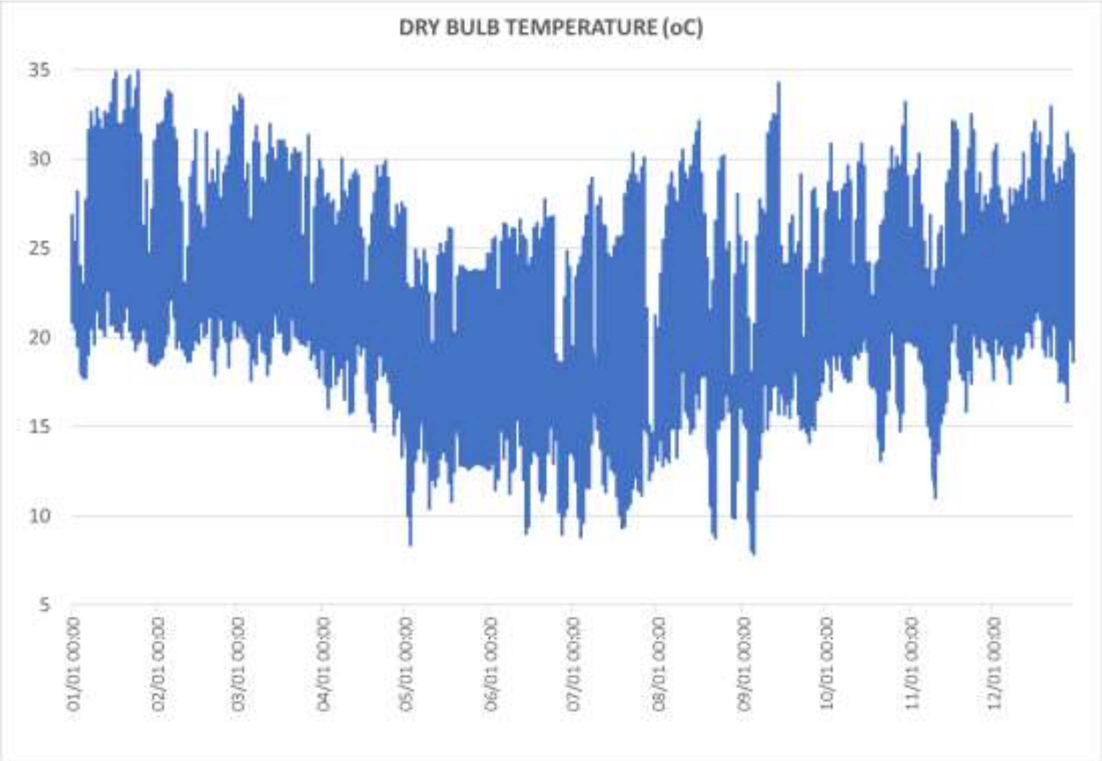

Figure 3 – Campinas annual DBT (^{o}C)

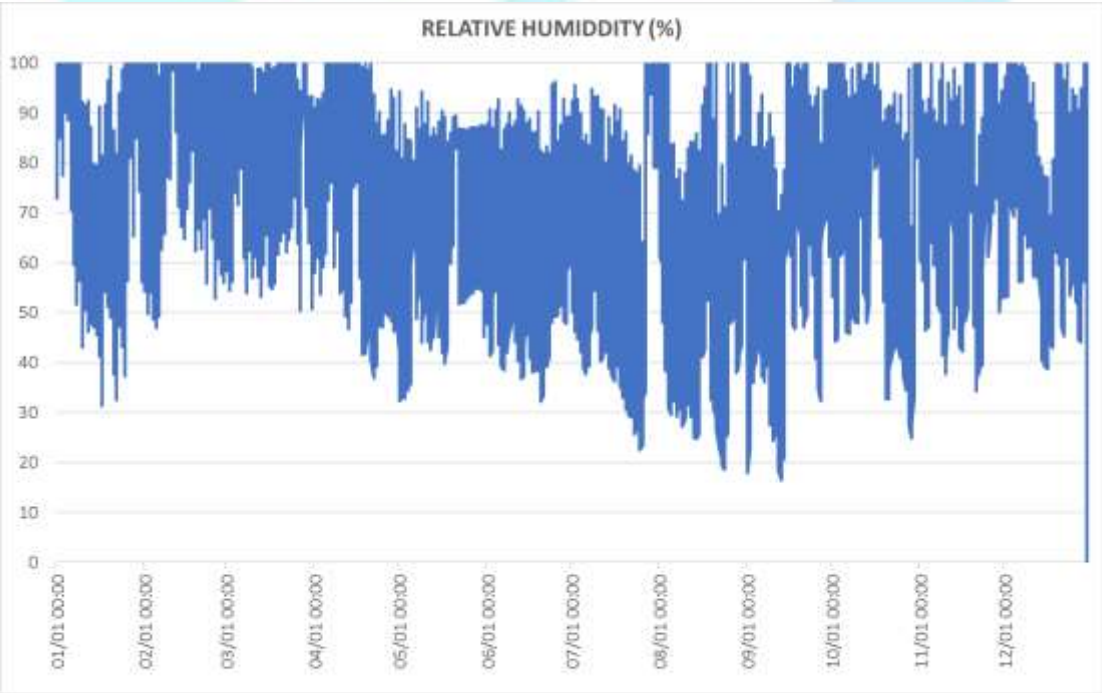

Figure 4 – Campinas annual RH (%)

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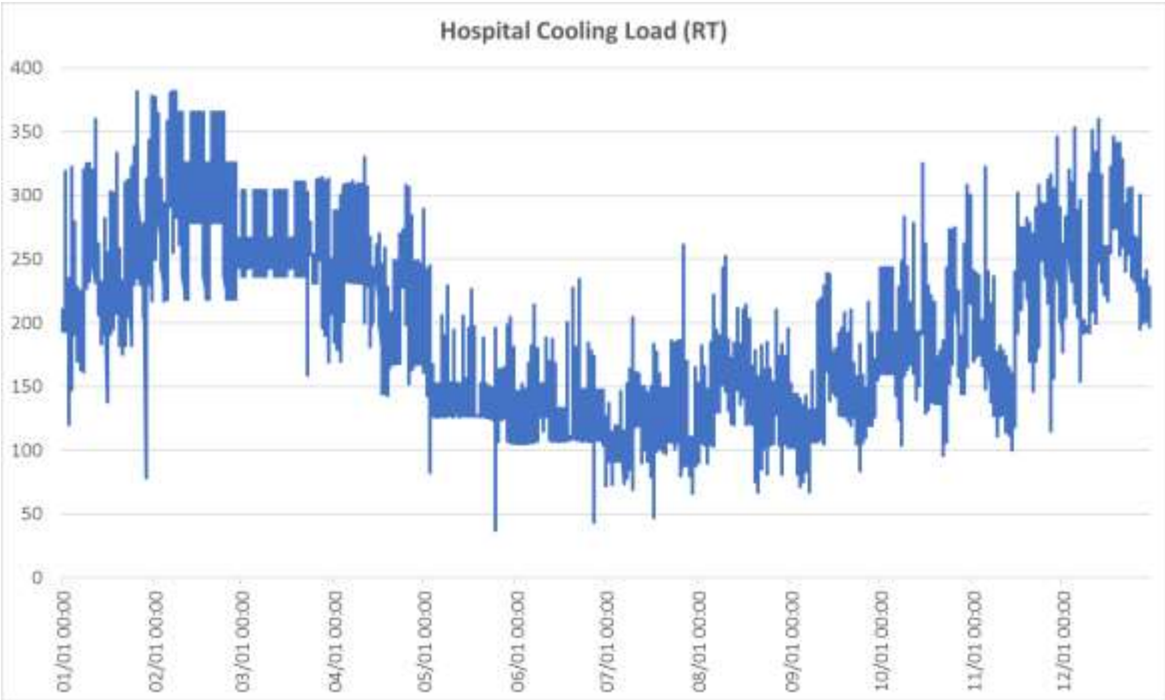

Figure 5 – Hospital HVAC cooling load (RT)

Figure 6 reveals the hospital electricity purchase. As previously mentioned, no heating load was calculated. Cooling load occurs all year days, affecting the electricity demand due to electrical chiller operation. The data reveals that electricity demand is not lower than 7000 kW and has a peak of close to 2100 kW.

Sanitary use hot water consumption is revealed in figure 7. Fuelled heaters are used for sanitary use hot water production. Make-up water to the sanitary use hot water system is assumed to be at 22.2°C all year. Sanitary use hot water is heated to 50°C.

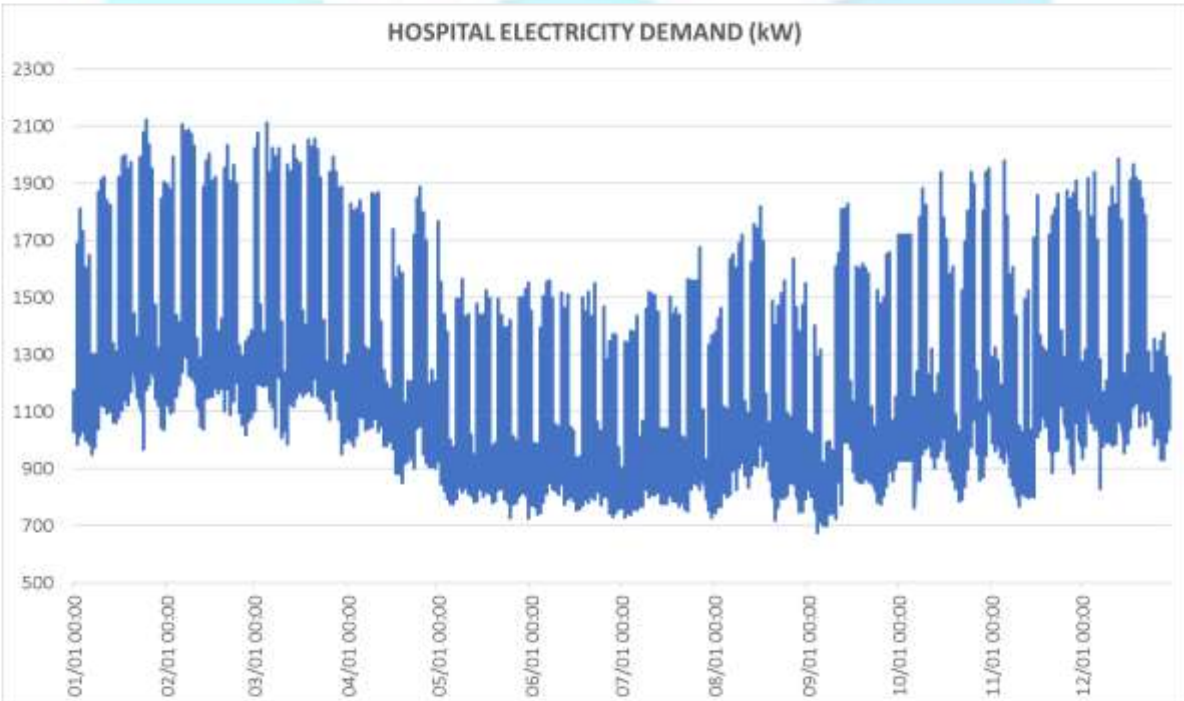

Figure 6 – Hospital electricity demand (kW)

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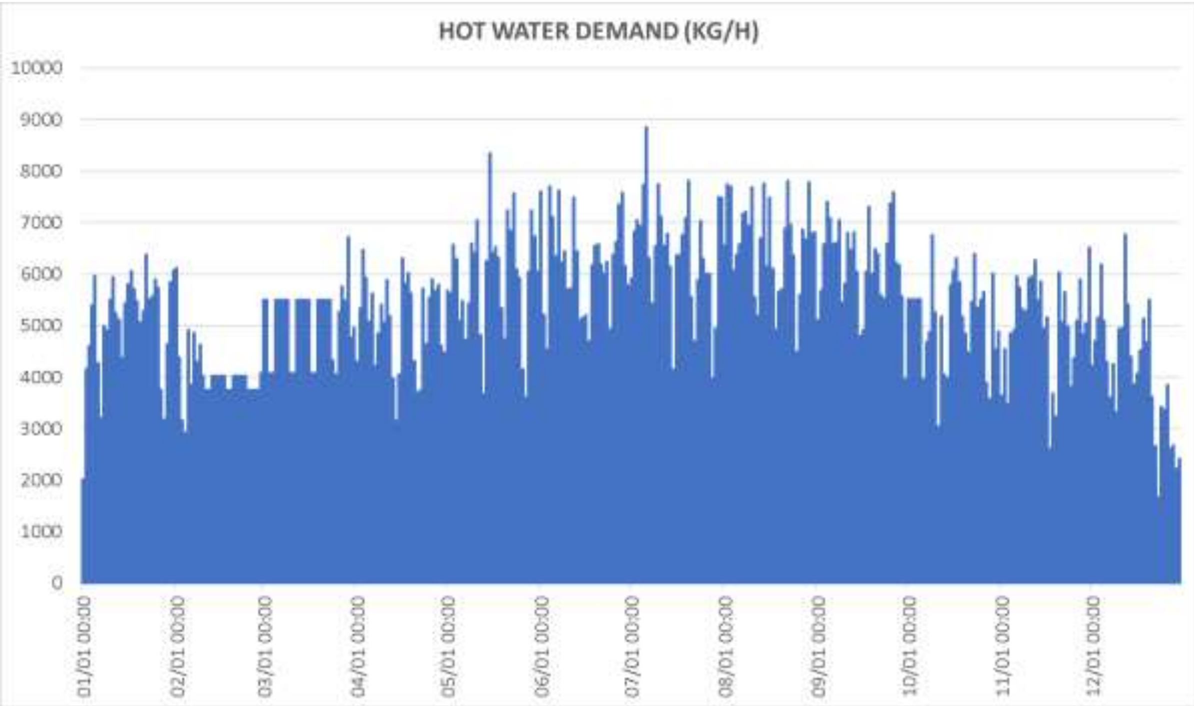

Figure 7 – Hospital sanitary use hot water demand (kg/h)

Figure 8 reveals the hospital steam demand. Peak values can be related to higher hospital activities and/or steam generator blowdown.

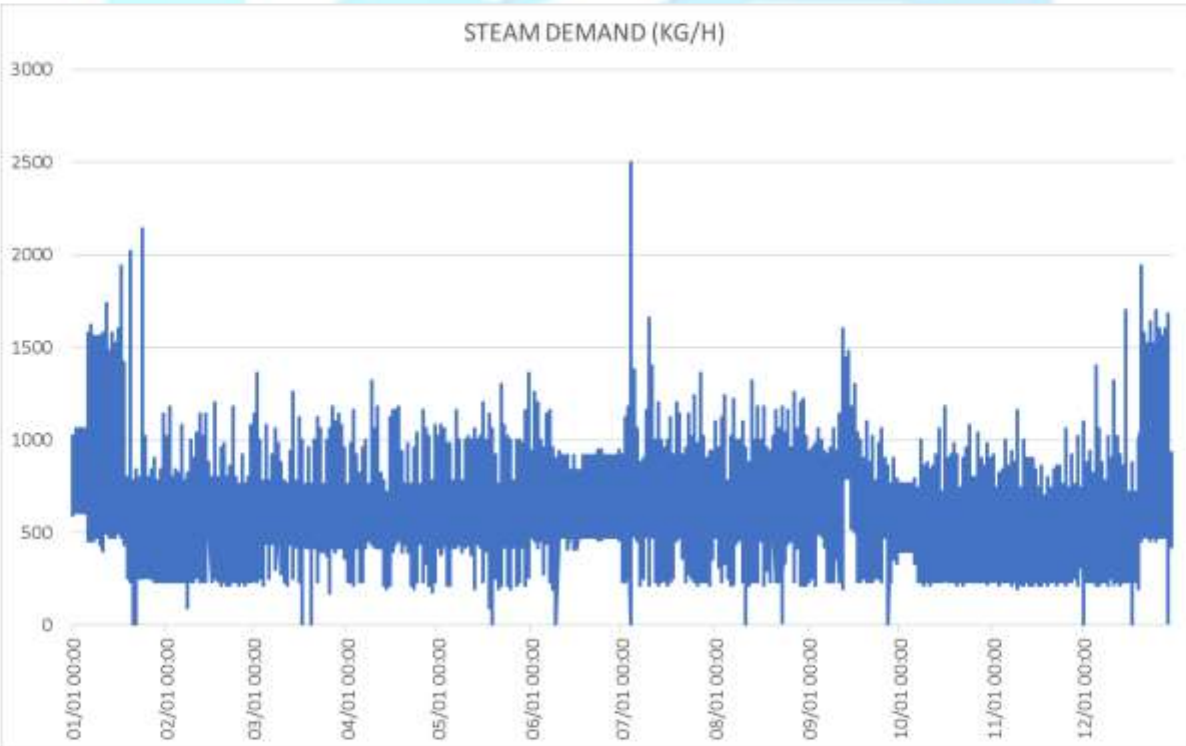

Figure 8 – Hospital annual steam demand (kg/h)

In summary, the hospital consumes 10,786,386 kWh/year of electricity, 578,115 kWh/year of sanitary use hot water and 3,794,581 kWh/year of steam, resulting in an annual building energy consumption of 271 kWh/m^2 per year (no energy conversion efficiency).

Figure 9 reveals the simulated engine CHP scheme. This proposed scheme allows the production of (i) chilled water for space cooling (flows 16 and 17) at a hot water absorption chiller (single effect), (ii) steam (flow 23), (iii) hot water (flows 12 to 15) and electricity.

Sanitary use low-temperature hot water is produced at HE1 and HE2 (flows 12 to 15) – HE2 and HE1 is in a series arrangement.

Engine primary circuit (PC) recovers energy from the engine jacket (flows 7 to 2) and uses it at the hot water absorption chiller generator. Engine exhaust gases are used in an HRSG (heat recovery steam generator) – flows 23. PC unused energy can be used at HE1 (flow 4 to 5), but if not used it is rejected on the PC air cooler (flows 5 to 6). Secondary circuit (SC) energy is recovered at HE2 – flow 8 to 9. SC unused energy is rejected on SC air cooler.

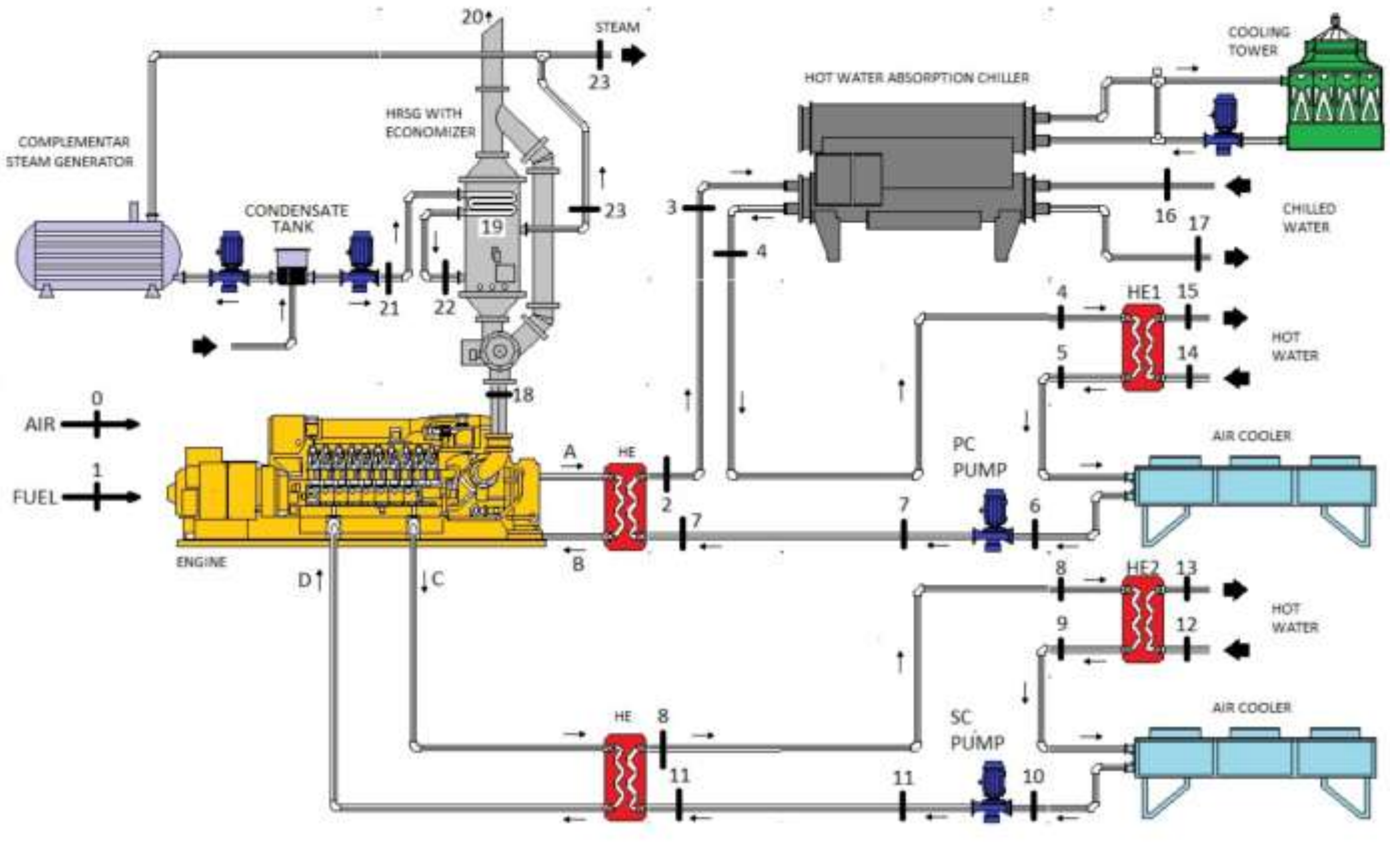

Figure 9 – engine CHP scheme

Figure 10 is a variant of the figure 9 engine CHP scheme. The only difference is that before opening the HRSG exhaust gas by-pass valve, the unused steam is enthalpically expanded and directed to the jacket water reheat heat exchanger. It allows the absorption chiller to produce more capacity due to a higher input hot water temperature.

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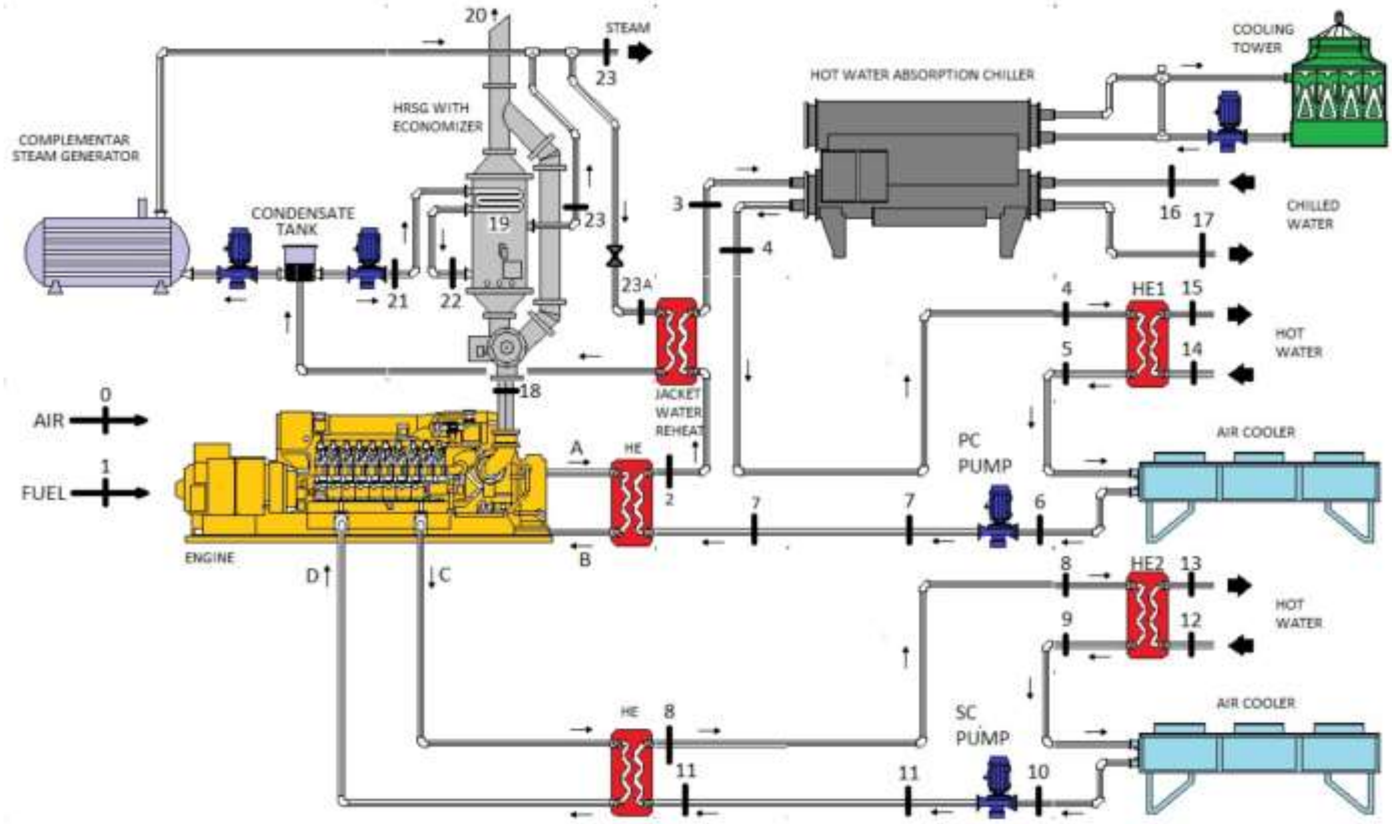

Figure 10 – engine CHP scheme

JACKET WATER REHEATS THERMODYNAMICS

T3 =	?	°C	TEMPERATURE LEAVING REHEAT HE
M3 =	14.68	kg/s	JACKET WATER FLOW IN KG/S
T2 =	93	°C	WATER TEMPERATURE ENTERING REHEAT HE
SH =	4.18	kJ/kg°C	AVERAGE WATER SPECIFIC HEAT
H 23 = H 23A =	2763	kJ/kg	STEAM ENTHALPY ENTERING REHEAT HE 90 psig = 7.098 bar
H 23B =	506.27	kJ/kg	LIQUID WATER ENTHALPY LEAVING REHEAT 14.7 psig = 2.028 bar

REHEAT STEAM FLOW KG/H	T3 (oC)
10	93.10216
50	93.51079
100	94.02159
150	94.53238
200	95.04317
300	96.06476
400	97.08634
500	98.10793
600	99.12951
700	100.1511
800	101.1727
900	102.1943

$$\dot{m}_v.(h_s - h_{sl}) = \dot{m}_{PC}.c_{pw}.(T_{flow3} - T_{flow2})$$

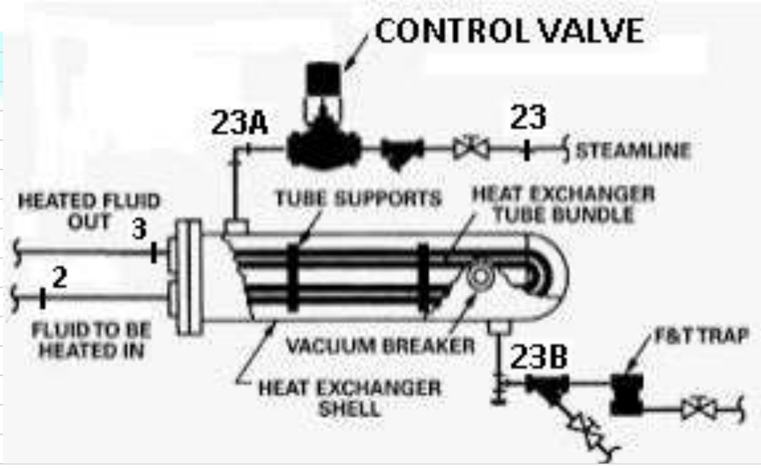

Figure 11 – jacket water reheats thermodynamics – using 1560 kW engine

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Sisterm THERMAL SYSTEMS

COGMCI GETTING THE MOST FROM A CHP DESIGN & ANALYSIS

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Table 1 – engine CHP thermodynamic properties – summer mode

	800 kW ENGINE				1200 kW ENGINE				1560 kW ENGINE			
flow number	pressure (kPa)	Temp (oC)	flow (kg/s)	enthalpy (kJ/kg)	pressure (kPa)	Temp (oC)	flow (kg/s)	enthalpy (kJ/kg)	pressure (kPa)	Temp (oC)	flow (kg/s)	enthalpy (kJ/kg)
0	100	25.00	1.189	298.80	100	25.00	1.753	298.80	100	25.00	2.306	298.80
1	100	25.00	0.042	45462	100	25.00	0.061	45462	100	25.00	0.080	45462
2	425	92.00	11.439	385.63	425	93.00	11.188	389.84	425	93.00	14.680	389.84
3	350	92.00	11.439	385.57	350	93.00	11.188	389.78	350	93.00	14.680	389.78
4	275	84.90	11.439	355.67	275	81.61	11.188	341.84	275	81.18	14.680	340.05
5	200	84.00	11.439	351.83	200	80.00	11.188	335.04	200	80.00	14.680	335.04
6	200	84.00	11.439	351.83	200	80.00	11.188	335.04	200	80.00	14.680	335.04
7	500	84.00	11.439	352.07	500	80.00	11.188	335.28	500	80.00	14.680	335.28
8	250	46.00	2.301	192.74	250	43.00	9.264	180.21	250	44.00	8.683	184.39
9	150	40.00	2.301	167.58	150	40.00	9.264	167.58	150	40.00	8.683	167.58
10	150	40.00	2.301	167.58	150	40.00	9.264	167.58	150	40.00	8.683	167.58
11	350	40.00	2.301	167.76	350	40.00	9.264	167.76	350	40.00	8.683	167.76
12	300	20.00	0.805	84.15	300	20.00	1.528	84.15	300	20.00	1.736	84.15
13	250	37.15	0.805	155.76	250	38.19	1.528	160.12	250	40.00	1.736	167.68
14	250	37.15	0.805	155.76	250	38.19	1.528	160.12	250	40.00	1.736	167.68
15	200	50.00	0.805	209.42	200	50.00	1.528	209.42	200	50.00	1.736	209.42
16	400	13.33	10.789	56.35	400	13.33	16.838	56.35	400	13.33	22.898	56.35
17	300	7.22	10.789	30.64	300	7.22	16.838	30.64	300	7.22	22.898	30.64
18	102	488.00	1.232	812.81	102	414.00	1.814	728.83	102	420.00	2.386	735.58
19	101	172.03	1.232	464.09	101	171.19	1.814	463.18	101	170.97	2.386	462.95
20	100	113.94	1.232	402.45	100	126.94	1.814	416.21	100	125.58	2.386	414.77
21	823.20	70.00	0.21	293.62	823.20	70.00	0.23	293.62	823.20	70.00	0.31	293.62
22	721.85	156.20	0.21	659.08	721.85	156.20	0.23	659.08	721.85	156.20	0.31	659.08
23	721.85	166.20	0.20	2763.28	721.85	166.20	0.23	2763.28	721.85	166.20	0.30	2763.28

Table 2 – engine CHP energy balance – summer mode

	800 kW ENGINE		1200 kW ENGINE		1560 kW ENGINE	
	(kW)	(%)	(kW)	(%)	(kW)	(%)
hot water SC	57.65	3.00	116.09	4.20	145.01	4.00
hot water PC	43.20	2.25	75.33	2.72	72.47	2.00
chilled water	277.41	14.43	432.94	15.66	588.75	16.23
steam	496.40	25.81	555.67	20.10	750.77	20.69
power	784.00	40.77	1176.00	42.53	1528.80	42.14
SUM	1658.65	86.25	2356.03	85.21	3085.81	85.06

Table 3 – HRSG design data

HRSG DESIGN	800 kW	1200 kW	1560 kW
number of tubes	160	140	190
inner diameter (mm)	25.4	31.75	31.75
outer diameter (mm)	31.75	38.1	38.1
tubes lenght (mm)	6.1	7.9	8
number of passes	1	1	1
pressure drop (mmwc)	154	173	164
Pinch point (oC)	5.83	4.99	4.77
economizer approach (oC)	10	10	10

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Table 1 reveals the engine CHP design thermodynamics. Three engines are being evaluated in this study (i) 800 kW, (ii) 1200 kW, and (iii) 1560 kW. They have a different energy balance, electrical efficiency, and PC and SC design temperatures (engine manufacturer constraint).

Exhaust gases being discharged to the atmosphere is cooled to 113ºC (800 kW), 126ºC (1200 kW), and 125ºC (1560 kW) – flow 20. Several factors affect the design exhaust gas temperature discharged to the atmosphere, including (i) entering flow and temperature in the HRSG, (ii) steam pressure, (iii) economizer approach, (iv) HRSG design data – table 3.

Absorption chiller is selected to operate with the same condition of the screw compressor chillers already installed at the hospital (i) chilled water between 7 and 12ºC and (ii) cooling tower water between 35 and 29ºC. The absorption chiller COP is assumed as 0.8 at the design condition – table 1.

Heat exchangers HE1 and HE2 are designed and simulated using the NTU method assuming a peak demand of 9000 kg/h. HE1 is designed for warming water from 30ºC to 50ºC. HE2 is designed to warm water from 22ºC to 40ºC. HE1 and HE2 are in a series arrangement looking to meet the hospital design condition for sanitary hot water use.

Table 2 reveals the three different engine energy balance producing electricity, steam, hot water, and chilled water.

The 800 kW engine CHP system produces 784 kW (40.77% electrical efficiency) of net electricity (2% is parasitic power – fans and pumps), 277.41 kW of chilled water at the absorption chiller (14.43%), 100.85 kW of sanitary use hot water (5.25%) and 496.4 kW of steam (25.81%). A EUF equal to 86.25% can be reached – table 2.

The 1200 kW engine CHP system produces 1176 kW (42.53% electrical efficiency) of net electricity (2% is parasitic power), 432.94 kW of chilled water at the absorption chiller (15.66%), 191.42 kW of sanitary use hot water (6.92%) and 555.67 kW of steam (20.10%). A EUF equal to 85.21% can be reached – table 2.

The 1560 kW engine CHP system produces 1528.8 kW (42.14% electrical efficiency) of net electricity, 588.75 kW of chilled water at the absorption chiller (16.234%), 217.48 kW of sanitary use hot water (6%), and 750.77 kW of steam (20.69%). A EUF equal to 85.06% can be reached – table 2.

Figure 11 reveals the primary circuit water reheats thermodynamics. The 1560 kW engine is used for the reheat analysis since more steam is produced. The steam control valve controlled by the PLC system is adjusted to open if (i) the electrical chillers are being used and (ii) the pressure in the steam distribution pipe reaches 1 bar above the design pressure (7 bar). It should remain open while the steam pressure is higher than the design pressure. This strategy allows the use of excedent steam to reheat the jacket water (flow 2) going to the absorption chiller – allowing a high capacity in the absorption chiller. Figure 11 reveals that 10 kg/h of excedent steam can warm the PC water leaving the engine (flow 20) by 0.1ºC and 100 kg/h can warm PC flow by 1ºC.

What happens in the absorption chiller when receiving a high temperature input flow? Hot water absorption chiller capacity is affected by the input water temperature since in the solution side of the absorption chiller generator more water is evaporated from the LiBr-H2O solution – maintaining a constant hot water flow. Entering with a high temperature hot water in a defined absorption chiller generator (selected for a lower input temperature) also affects the water temperature leaving the absorption chiller – flow 4. Figure 12 reveals the influence of higher input water temperatures in the absorption chiller using the 1560 kW engine. At point 118 the absorption chiller operates at its design condition - flow 3 at 93ºC and flow 4 at 81.2ºC – a temperature difference of 11.8ºC and a capacity of 167.1 RT (588 kW). At point 94 excedent steam is used to warm the PC hot water from 93ºC to 101.8ºC (flow 3). PC hot water leaves the absorption chiller generator at 86.4ºC – a temperature difference of 15.4ºC and 220.6 RT (776.5 kW) capacity. A 30% rise in the hot water temperature difference resulted in a 32% higher capacity – higher hot water input temperatures also raise the absorption chiller COP.

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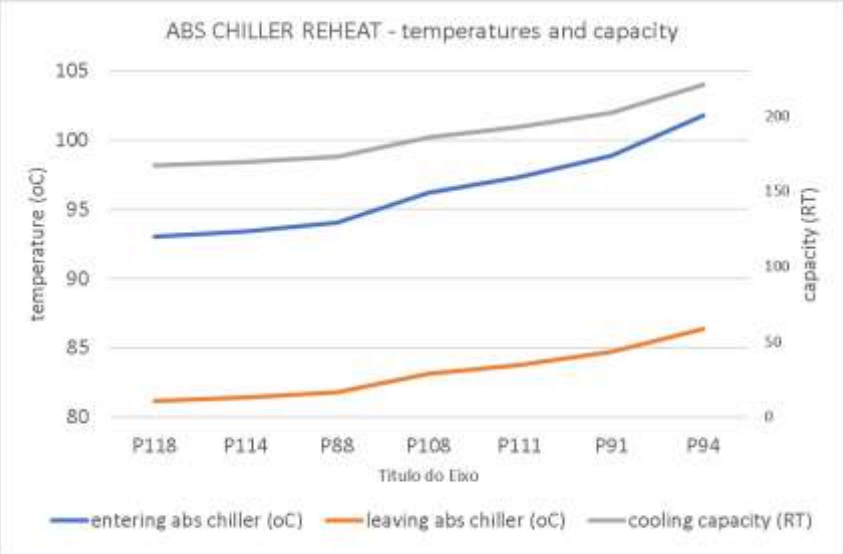

Figure 12 – absorption chiller at higher hot water temperature input

8 different solutions are evaluated:

- Case 1: one 800 kW engine CHP system operating at full load.
- Case 2: one 1200 kW engine CHP system operating at full load.
- Case 3: one 1560 kW engine CHP system operating at full load.
-
- Case 4: one 1560 kW engine CHP system operating at electrical dispatch.
-
- Case 5: one 1560 kW engine CHP system operating at electrical dispatch and jacket water reheat.
-
- Case 6: one 1560 kW engine CHP system operating at thermal dispatch and jacket water reheat with 70% minimum EUF.
-
- Case 7: one 1560 kW engine CHP system operating at thermal dispatch and jacket water reheat with 80% minimum EUF.
-
- Case 8: one 1560 kW engine CHP system operating at full load and jacket water reheat.

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Table 4 – General Results

		CASE 1	CASE 2	CASE 3	CASE 4	CASE 5	CASE 6	CASE 7	CASE 8
		800FL	1200FL	1560FL	1560ED	1560EDreheat	1560TD70reheat	1560TD80reheat	1560FLreheat
	ELECTRICITY								
1	electricity consumption (kWh/year) =	10,786,386.83	10,786,386.83	10,786,386.83	10,786,386.83	10,786,386.83	10,786,386.83	10,786,386.83	10,786,386.83
2	electricity production (kWh/year) =	6,981,666.22	10,472,499.36	13,614,249.15	9,880,102.43	9,759,044.70	12,604,851.31	9,293,011.36	13,614,249.15
3	electricity production - net (kWh/year) =	6,842,032.90	10,263,049.37	13,341,964.18	9,685,519.33	9,566,817.04	12,352,754.29	9,107,151.14	13,341,964.18
4	avoided electricity abs chiller (KWh/year) =	550,471.39	844,315.56	1,066,885.64	924,482.58	1,068,217.31	1,166,931.85	1,046,060.63	1,170,831.85
5	adittional electricity (kWh/year) =	3,393,882.54	-320,978.10	-3,622,463.00	176,384.91	151,352.47	-2,733,299.32	633,175.05	-3,726,409.20
6	PEC without cog/trigeneration (kWh/year) =	23,969,748.50	23,969,748.50	23,969,748.50	23,969,748.50	23,969,748.50	23,969,748.50	23,969,748.50	23,969,748.50
7	engine fuel consumption (kWh/year) =	16,774,823.85	24,107,990.44	31,690,554.29	23,792,529.86	23,536,057.83	29,552,418.85	22,537,665.98	31,690,554.29
8	PEC surplus/exported elect (kWh/year) =	7,541,961.21	-713,284.67	-8,049,917.77	391,966.47	336,338.83	-6,073,998.48	1,407,055.67	-8,280,909.34
9	PEC with cog/trigeneration (kWh/year) =	24,316,785.06	23,394,705.77	23,640,636.52	24,184,496.32	23,872,396.66	23,478,420.38	23,944,721.65	23,409,644.95
	HOT WATER								
10	Hot water consumption SC (kWh/year) =	578,115.15	578,115.15	578,115.15	578,115.15	578,115.15	578,115.15	578,115.15	578,115.15
11	Hot water production PC (kWh/year) =	179,749.57	203,834.22	169,812.32	100,183.33	134,582.33	172,769.57	153,476.99	171,936.80
12	Hot water production SC (kWh/year) =	249,435.40	359,305.86	405,631.18	385,048.90	384,308.10	403,690.34	383,843.72	405,631.18
13	aditional hot water SC+PC (kWh/year) =	148,930.17	14,975.06	2,671.64	92,882.91	59,224.72	1,655.24	40,794.43	547.16
14	PEC without cog/trig (kWh/year) =	628,386.03	628,386.03	628,386.03	628,386.03	628,386.03	628,386.03	628,386.03	628,386.03
15	PEC with cog/trig (kWh/year) =	161,880.62	16,277.24	2,903.96	100,959.69	64,374.70	1,799.17	44,341.77	594.74
	STEAM								
16	Steam consumption (kg/h/year) =	5,531,188.76	5,531,188.76	5,531,188.76	5,531,188.76	5,531,188.76	5,531,188.76	5,531,188.76	5,531,188.76
17	Steam production (kg/h/year) =	5,072,330.47	5,243,451.87	5,470,432.55	5,380,657.14	5,373,748.43	5,462,392.90	5,457,131.11	5,462,398.15
18	aditional steam (kg/h/year) =	458,858.29	287,736.88	60,756.20	150,531.62	157,440.33	68,795.86	74,057.65	68,790.61
19	Steam consumption (kWh/year) =	3,794,581.72	3,794,581.72	3,794,581.72	3,794,581.72	3,794,581.72	3,794,581.72	3,794,581.72	3,794,581.72
20	Steam production (kWh/year) =	3,479,789.49	3,597,184.53	3,752,900.92	3,691,311.97	3,686,572.36	3,747,385.45	3,743,775.68	3,747,389.05
21	Aditional steam (kWh/year) =	314,792.24	197,397.19	41,680.80	103,269.76	108,009.37	47,196.27	50,806.04	47,192.67
22	PEC withou cog/Trig (kWh/year) =	4,124,545.35	4,124,545.35	4,124,545.35	4,124,545.35	4,124,545.35	4,124,545.35	4,124,545.35	4,216,201.92
23	PEC with cog/trig (kWh/year) =	342,165.48	214,562.16	45,305.22	112,249.74	117,401.48	51,300.30	55,223.96	52,436.30
	CHILLED WATER								
24	Chilled water demand (RT) =	1,751,462.21	1,751,462.21	1,751,462.21	1,751,462.21	1,751,462.21	1,751,462.21	1,751,462.21	1,751,462.21
25	chilled water production (RT) =	688,087.60	1,055,394.44	1,333,608.71	1,155,603.18	1,335,271.70	1,458,665.40	1,307,575.59	1,463,540.30
26	cooling load attended (%)	39.29%	60.26%	76.14%	65.98%	76.24%	83.28%	74.66%	83.56%
	EUF, ENGINE LOAD AND PAYBACK								
27	EUF	78.59	75.28	70.61	75.26	78.48	73.59	79.64	72.05
28	ENGINE LOAD	100.00	100.00	100.00	72.64	71.75	92.61	68.32	100.00
29	PAYBACK	1.27	1.31	1.34	1.78	1.76	1.42	1.84	1.33
	COMPLETE PES								
30	PEC without cog/trig (kWh/year) =	28,722,679.88	28,722,679.88	28,722,679.88	28,722,679.88	28,722,679.88	28,722,679.88	28,722,679.88	28,814,336.44
31	PEC with cog/trig (kWh/year) =	24,820,831.16	23,625,545.18	23,688,845.70	24,397,705.75	24,054,172.84	23,531,519.85	24,044,287.38	23,462,676.00
32	PES (%) =	13.58%	17.75%	17.53%	15.06%	16.25%	18.07%	16.29%	18.57%
	EUROPEAN UNION DIRECTIVE - PES								
33	PES EU Directive (no grid loss - 53%) (%) =	15.24	13.67	9.41	12.64	15.13	12.01	16.03	10.67
34	PES < 0.45 kV (%)=	23.93	22.94	18.83	21.83	23.81	21.00	24.49	19.83
35	PES < 12 kV (%) =	21.50	20.36	16.23	19.27	21.39	18.51	22.13	17.29
	EQUIVALENT THERMAL EFFICIENCY								
36	ETE (no grid loss) =	59.02%	56.71%	53.39%	55.11%	56.08%	54.40%	56.77%	53.77%
37	ETE (10% grid loss) =	65.58%	63.01%	59.33%	61.23%	62.31%	60.44%	63.08%	59.75%
38	ETE (20% grid loss) =	73.77%	70.89%	66.74%	68.89%	70.10%	68.00%	70.96%	67.21%

Results Discussion

Table 4 reveals the engine CHP cases main results.

In the simulation analysis, the lower engine load is limited to 50% (default value).

Primary energy savings analysis (annex I and II) assumes boilers and steam generators with 92% efficiency and thermal plants with 53% thermal efficiency disregarding grid losses and close to 45% thermal efficiency taken grid losses into account (EU directive values) [3-4].

Line 1 reveals the hospital annual electricity consumption (kWh/year), calculated using figure 6 (data acquisition system). Line 2 reveals the CHP cases annual power production (kWh/year) and line 3 reveals the engine CHP net electricity production. Line 4 reveals the avoided electricity in the electrical chillers due to the absorption chiller use. Line 5 reveals the need for surplus electricity or the electricity export to the grid. Case 1 produces about 70% of the electricity consumption (line 1) – it can be defined as an electricity base load solution with the engine at full load all the time. In cases 2 and 3 the engine also operates at full load, case 2 produces about 3% more electricity than the hospital consumption, and case 3 produces about 35% excedent electricity.

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Cases 4 and 5 operate at electrical dispatch - engine load is modulated to avoid exported electricity to the grid. In case 5 the PC water (flow 2) is reheated using excedent steam and more capacity is obtained in the absorption chiller. Both need surplus electricity from the grid – peak electricity demand hours. Case 5 produced less electricity than case 4 and produced more capacity in the absorption chiller, needing less grid surplus electricity while consuming less fuel (line 7).

Cases 6 and 7 operate at thermal dispatch with PC (flow 2) reheat (using excedent steam). In case 6 a EUF equal to 70% is to be maintained and in case 7 a EUF equal to 80% is the goal. Case 6 produces more electricity since it is easier to reach a 70% EUF. The average engine load is 92.6% for case 6 and 68.3% for case 7. More electrical consumption is avoided at the electrical chillers due to the absorption chillers use when the engine operates at higher loads.

In case 8 the engine operates at full load with PC (flow 2) reheat (using excedent steam). Compared to case 3, about 3% more electricity is exported to the grid due to PC (flow) 2 reheat.

Figure 13 reveals the demand and power produced by all cases. There are a lot of data to be displayed in a unique graph (superimposed results hide a lot of data). To demonstrate the results "polynomial tendency curves" were created. Cases 1, 2, 3, and 8 operate at full load and the produced power is very close to their nominal power – a small reduction is verified at high ambient dry bulb temperatures. Cases 4 and 5 have similar behavior since both engines operate at electrical dispatch, a lower engine load is verified at case 5 since PC (flow 2) reheat rises the absorption chiller production and reduces the electrical chiller use. Case 6 operates at a higher load since it is easier to reach a 70% EUF than an 80% EUF. Both cases reveal a reduction in power production in the winter months (south hemisphere) since the cooling load is reduced.

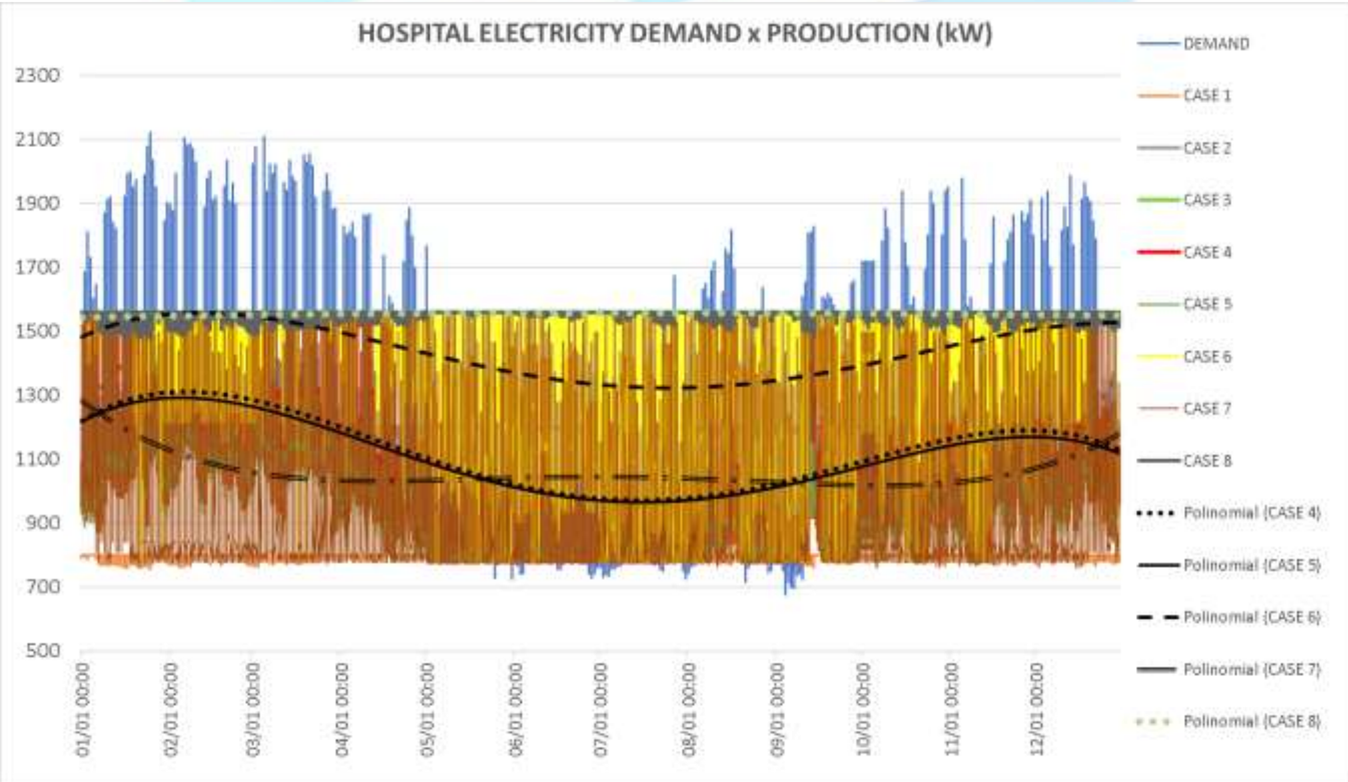

Figure 13 – electricity demand and production

Figure 14 reveals the engine load for all cases. The tendency curves have similar behavior of figure 13.

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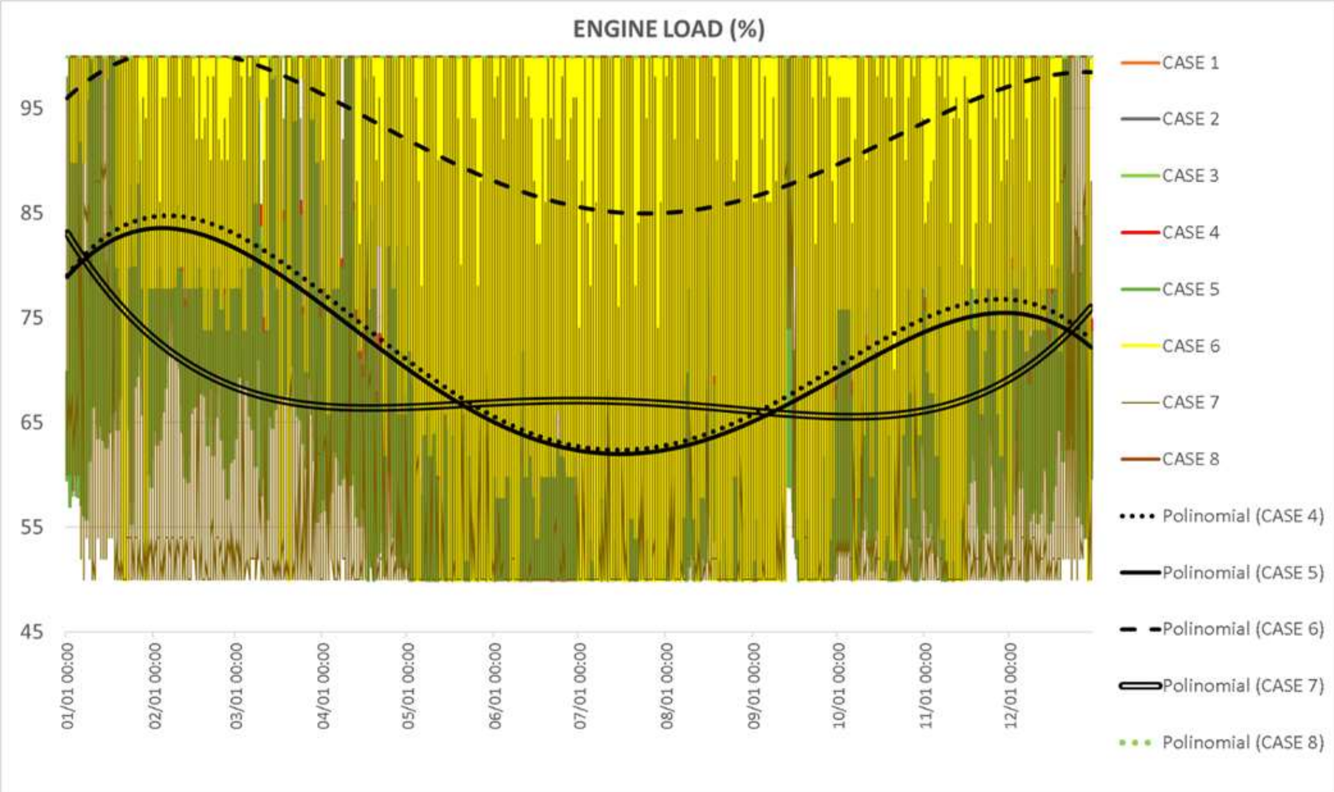

Figure 14 – engine load (%)

Line 6 reveals the primary energy consumption (PEC) assuming that electricity is produced by a 45% efficiency thermal plant (it is equal for all cases) – line 1 is divided by 0.45.

Line 8 reveals the PEC associated with the electricity surplus or export to the grid. Line 5 is divided by 0.45 assuming surplus electricity is produced by a 45% efficiency thermal plant and that exported electricity avoids electricity production at a 45% efficiency thermal plant.

Line 9 is the sum of lines 7 and 8. It represents how much fuel is needed to attend the hospital electrical consumption (kWh/year) taking credit for the exported electricity. Cases with higher absorption chiller production and more exported electricity have a lower PEC.

Line 10 represents the hospital annual sanitary use hot water consumption (figure 7). Lines 11 and 12 show how much energy is being recovered by HE1 and HE2 respectively. Line 13 shows the surplus energy to attend the sanitary use hot water consumption (line 10). Line 14 reveals the PEC to produce the hot water consumption in a 92% efficiency boiler – line 10 is divided by 0.92. Line 15 reveals the additional PEC if the engine CHP system was installed – line 13 divided by 0.92.

Figure 15 reveals the engine CHP cases hot water demand and production. Hot water demand is zero or almost zero between midnight and 5 am, that is why the “tendency curves” are close to the figure base. Several factors affect the sanitary use of hot water production, including (i) the engine energy in the secondary circuit, (ii) the engine temperatures in the secondary circuit (flows 8 to 11), (iii) the amount of energy available from the engine primary circuit (temperatures of flows 4 – flow 5) for hot water production, (iv) heat exchangers HE1 and HE2 design, (v) flow 4 temperature at variable engine load and chilled water production (vi) engine load, among others. Cases 6 and 8 revealed better results since the engine operates at higher loads and PC (flow 2) is reheated by excedent steam, resulting in a higher flow 4 temperature arriving at HE1 (see figure 12).

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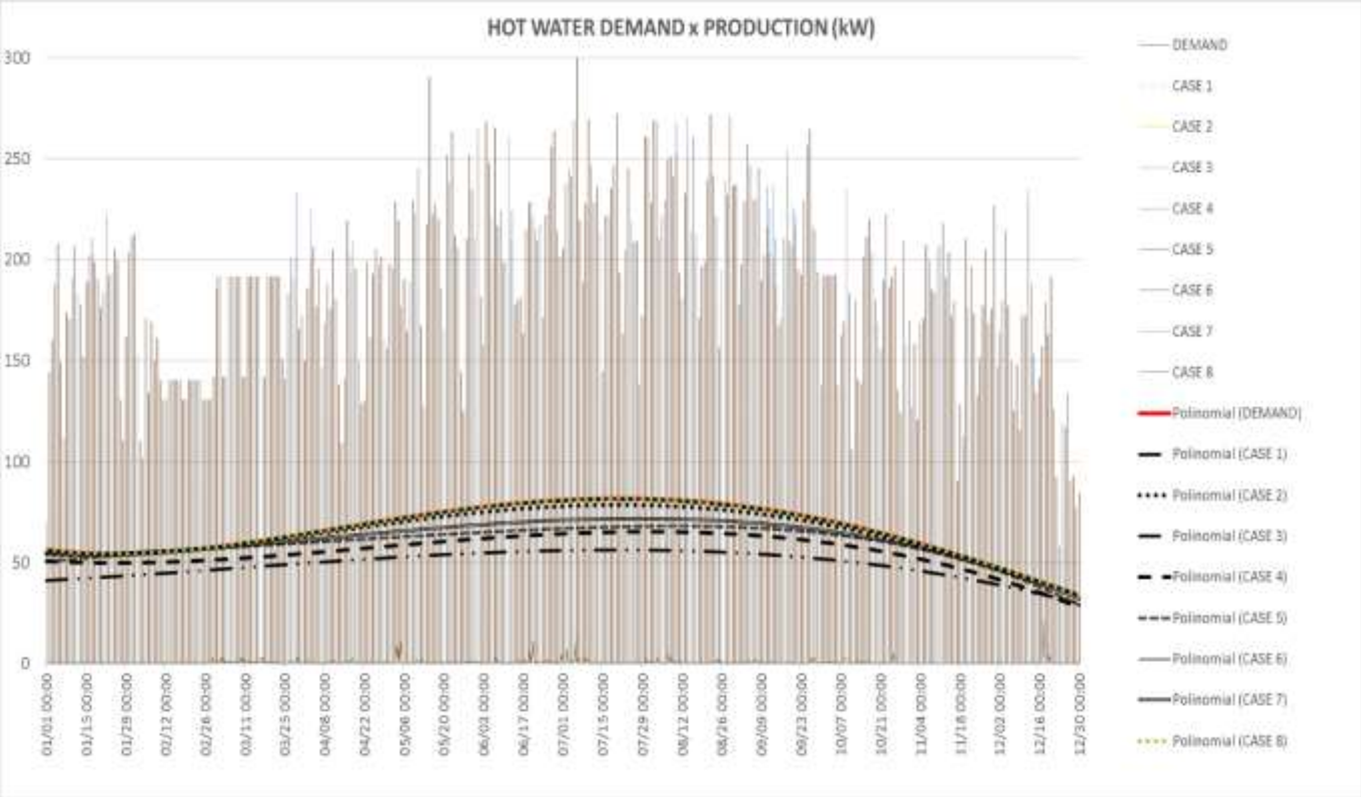

Figure 15 – sanitary use hot water demand and production

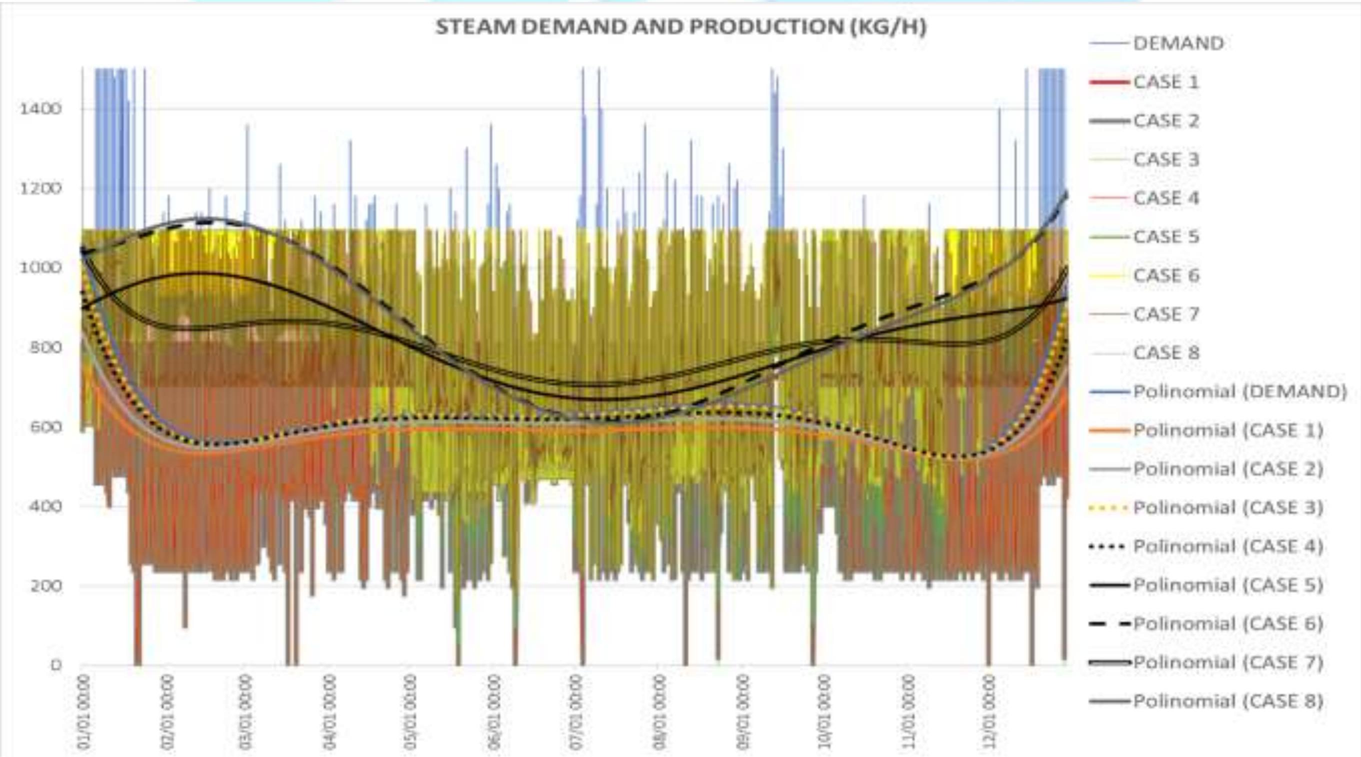

Figure 16 – steam demand and production

Line 16 reveals the annual steam consumption in kg/h/year (figure 8). Line 17 reveals the annual steam production and line 18 the additional steam to meet the consumption. Lines 19, 20, and 21 are similar, but they are on an energy basis (kWh/year). Case 1 produces about 92% of the steam consumption and case 2 about 96%. Cases 3 to 8 produces

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between 97 and 99% of the hospital needs. Line 22 reveals the PEC to attend line 19 steam consumption assuming a 92% efficiency steam generator – line 19 is divided by 0.92. Line 23 reveals the PEC if the engine CHP systems are adopted – line 21 is divided by 0.92.

Figure 16 reveals the steam demand and production. "Tendency curves" help us see the results. Cases 1, 2, and 3 almost met the steam demand. Case 4 attends a higher fraction of the steam consumption than cases 1 and 2, but less than case 3, since the 1560 kW engine operates at part load (electrical dispatch) at case 4. For the cases that make PC (flow 2) reheat with excedent steam (steam not demanded by the hospital) – cases 5 to 8 – the produced steam is the sum of the hospital consumed steam and the steam that is used for PC (flow 2) reheat. Case 5 uses more steam than case 4 since excedent steam (steam not demanded by the hospital) is used for PC (flow 2) reheat. Due to case 5 engine electrical dispatch operation (partload), excedent steam is also used in the winter months to raise the absorption chiller capacity looking to attend the cooling load. Cases 6 and 8 have similar results since both operate the engine at a high average load (table 4 line 28). Case 7 produced steam is connected to the engine load and the cooling load profile. All cases that use PC reheat, revealed a higher steam production in the summer months due to PC (flow 2) reheat looking to attend the cooling load.

Cases 5 and 7 produce more steam than the demand in the winter months since the engine operates at a reduced load and excedent steam is used for PC (flow 2) reheat to attend chilled water demand.

Line 24 reveals the hospital chilled water system annual cooling load (figure 5). Line 25 reveals the absorption chiller annual production. Line 26 reveals the percentage of the cooling load that is being attended by the absorption chiller. Case 1 produces 39% of the cooling load, case 2 produces 60% and cases 3 to 8 produces between 65 and 83% of the cooling load. Comparing cases 3 and 8 we can see that reheating flow 2 produced close to 10% more capacity in the absorption chiller. Line 4 results are equal to line 25 results multiplied by the existing screw chillers efficiency (0.8 kW/RT ~ COP=4.2).

Figure 17 reveals the cooling load and the absorption chiller production for all cases. "Tendency curves" help us understand the results. Case 1 is always at the base of the cooling load. In cases 2 to 8 the absorption chiller operates at the base of the cooling load in the summer, autumn, and spring months, but at part load at some winter hours. It can be seen that at some hours in February case 8 produces close to 235 RT (gray lines) while their nominal cooling production is 167 RT (table 2) – a 40% rise – see figure 12.

Figure 18 reveals the final EUF. Final EUF is the sum of (i) electricity, (ii) sanitary use hot water (ii), chilled water, and (iv) steam production that are effectively used by the hospital or exported to the grid (electricity). Steam used for PC reheat is not used on EUF calculation. A high coincidence of their production and use reveals the higher values. Case 1 operates in the baseload and has higher values in the winter months mostly due to higher sanitary use hot water demand – an average of 78.59% was calculated (Table 4). Case 2 reveals an almost constant EUF, with peaks in the graph corners (high steam demand) and a small reduction in the spring and autumn months. Case 3 revealed the lower annual EUF with most of their values between 68 and 72% - average is 70.61%.

Case 4 has peak values in summer (graph corners) due to high steam demands and high EUF in winter, since at winter the engine load is lower and a big fraction of the produced steam, hot water, and chilled water and is used – average EUF is 75%. Case 5 operates at a lower engine load than case 4, but since it uses excedent steam for PC (flow 2) reheat, more chilled water is produced, and more hot water is produced (flow 4 arrives at HE1 at a higher temperature) – average EUF is 78%. In case 6 the engine operates with a high load (92.6%) looking for a 70% thermal dispatch EUF, most of the results are close to 73% - average is 73.6%. In case 7 the engine operates looking for an 80% thermal dispatch EUF, engine load is the lower (68.3%) but EUF is the higher (average is 79.64%). A very flat tendency curve is revealed. Case 8 operates at full load as case 3 but reveals higher EUF results due to PC (flow 2) reheat. In winter the results are similar revealing that no steam is used for PC (flow 2) reheat – figure 16 also shows this.

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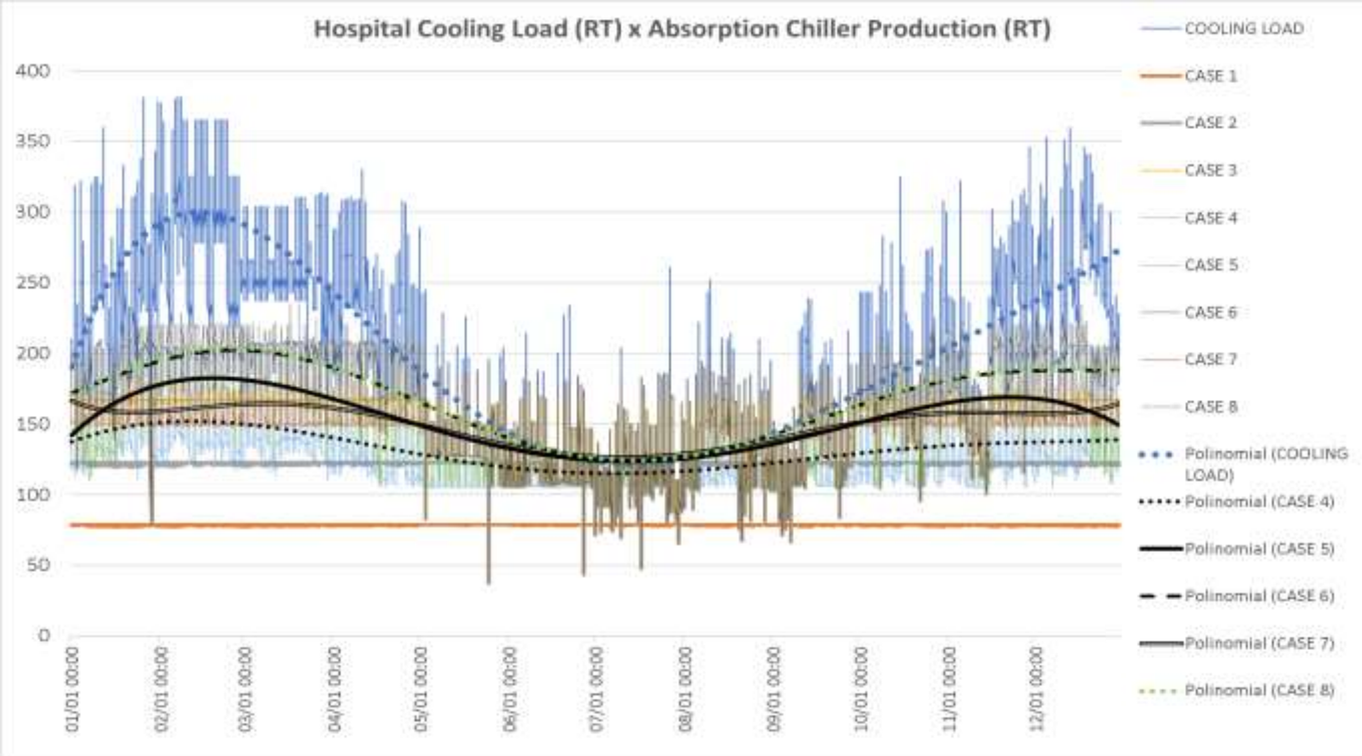

Figure 17 – cooling load and absorption chiller production

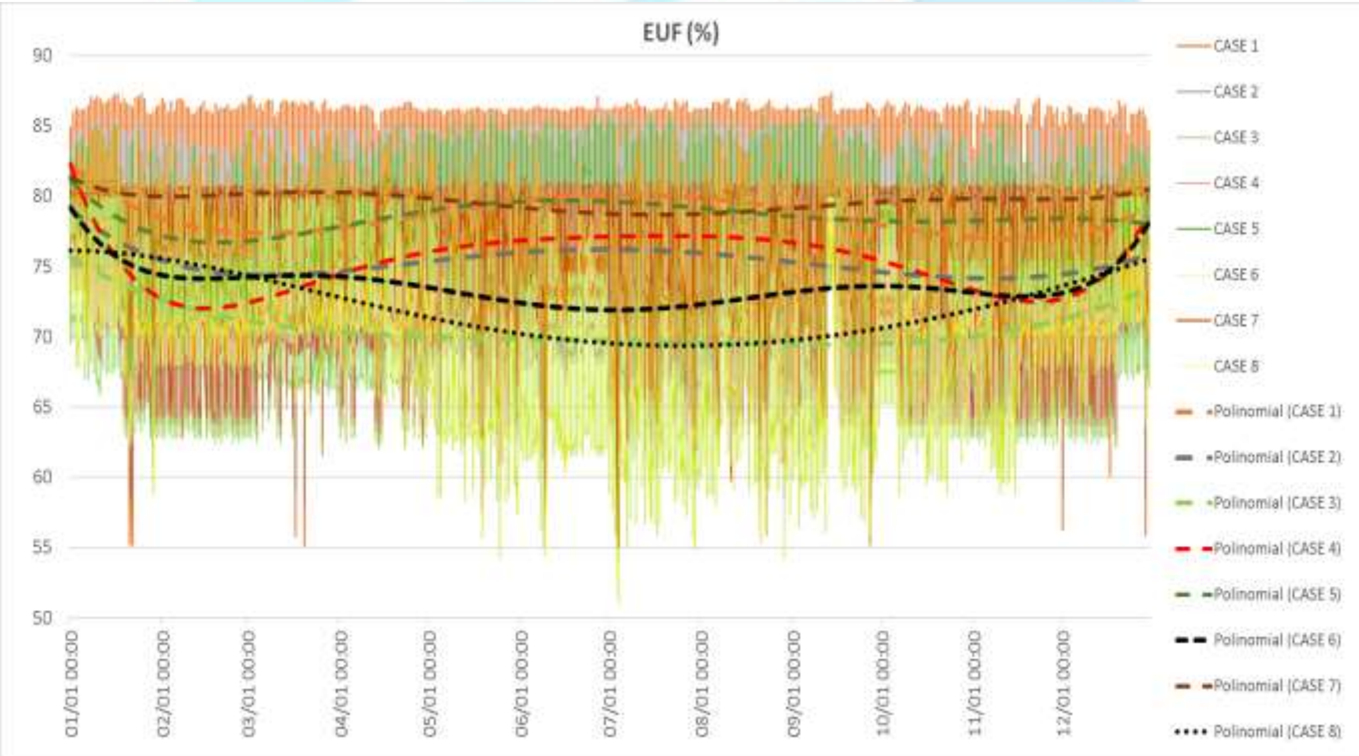

Figure 18 – final EUF

Line 27 reveals the annual average EUF. EUF is normally higher for smaller systems since smaller systems operate at the baseload and more residual energy is recovered. Electrical dispatch (cases 4 and 5) and thermal dispatch (cases 6 and 7) also revealed high annual EUF. Case 8 has a EUF 1.4% higher than case 3, due to flow 2 reheat using excedent steam. Engine average load and a payback period are revealed at lines 28 and 29 respectively. Excedent electricity is

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assumed to be sold to the grid at the same price the hospital buys it from the grid. Cases 3, 7 and 8 EUF details can be seen on annex III.

PES analysis is revealed at lines 30, 31, and 32. At line 30 the PEC of the hospital is calculated (line 6 + line 14 + line 22). Line 31 reveals the PEC with an engine CHP system (line 9 + line 15 + line 23). Line 32 reveals the PES as 13.6% for case 1, 17.5% for case 2, 15% for case 4 and between 16.25% and 18.57% for the remaining cases. The PES analysis reveals that under the thermal efficiency scenario utilized in this study as well as the defined grid loss, higher engine systems with jacket water reheat can save more primary energy – reduced CO2 emissions.

Lines 33, 34 and 35, evaluate the results under the EU Directive. Harmonized reference values for thermal efficiency are used. Line 33 uses thermal efficiency as 53% (no grid losses) while lines 34 and 35 assumes grid losses and a connection to the grid at a maximum 450V and 12000 V respectively. Normalized thermal efficiency between 45.1% and 45.7% ae used (450V) – depends on electricity import or export.

The EU directive is connected with EUF. Higher EUF reveals higher PES under the EU Directive. Case 7 revealed to be the best solution, accomplishing the (i) higher engine in this study, (ii) PC (flow 2) reheat, and (ii) a thermal dispatch operation with a very restrictive minimal EUF (80%).

Conclusions

This study uses annual real demand and consumption data (electricity, steam, chilled water, and hot water) from an existing hospital situated in a tropical climate to develop an engine CHP analysis. Tropical city buildings usually don´t need space heating and a high cooling load is verified in the summer months while intermediate cooling load occurs in spring, autumn, and winter. Cooling load can represent up to 40% of the building electricity consumption, at this study only the main chilled water system is being evaluated (figure 5), but the hospital has thousands of individual equipment included in the hospital electricity demand profile (figure 6).

A data acquisition system was implemented. Better instrumentation can improve the data collection system quality. The annual energy demands profiles and local weather data (DBT and RH) were used as input for the COGMCI software. Three different engine sizes at different operational modes and some of them with primary circuit hot water reheat were evaluated. Four main efficiency indicators were used to compare the results: (i) EUF, (ii) PES using the EU directive – annex II, (iii) PES – annex I, and (iv) ETE - equivalent thermal efficiency.

EUF is the most used CHP efficiency indicator. Although it reveals how much energy is being recovered it doesn't take into account the energy loads that are not attended by the CHP system.

PES using the European Directive (equation 17) was developed using the EUF definition. It also doesn't evaluate the thermal demands that are not being attended to, but it compares the CHP system performance with the technologies available for hot water, steam and electricity production. Electricity export and import and grid losses are evaluated.

Annex I PES analysis uses the equations directly obtained by an energy balance approach. It considers the (i) energy loads attended by the CHP system, (ii) the not attended energy loads, (ii) the efficiency for electricity, hot water, steam, and chilled water production, ((iv) allows CHP products export (electricity, hot water, steam and/or chilled water) and (v) the grid losses associated with centralized power systems.

ETE allows a comparison between the grid thermal plants and the proposed CHP systems.

The results are justified due to the engine electrical efficiency, energy balance, PC and SC water temperatures, exhaust gases flow and temperature at part and full load, site energy demands (sanitary use hot water, cooling, and

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electrical demands), and thermal equipment design. A complete results discussion requires a detailed analysis of COGMCI results. Thousands of data results were used in one single graph (superimposed lines) and tendency lines were used for a better results evaluation.

Comparing the full load operation (cases 1, 2, and 3), three of the efficiency indicators reveal case 1 as the best solution. PES using annex I formulation puts case 2 as the best solution, followed by case 3 (very close) and case 1.

Operating the 1560 kW engine at electrical dispatch (cases 4 and 5) rises the EUF, the PES (EU directive), and the ETE results, making them very similar to cases 1 and 2. Case 5 has better results than case 4 since excedent steam is used for primary circuit reheat (flow 2).

Thermal dispatch operation (cases 6 and 7) also rises the EUF, PES (EU directive), and the ETE. Case 7 revealed the higher EUF and PES using the EU directive. Thermal dispatch operation can be planned at different approaches: (i) outside air temperature forecast, (ii) real-time EUF, (iii) similar day benchmark, (iv) combination of different approaches in an algorithm.

PC water reheat (flow 2) rises all the efficiency indicators integrating the thermal energy demand and production. Some cases cannot be compared directly, since different operational modes also affect the results. Case 8 revealed to be the best solution when using the PES ANNEX I. PC reheat produced 7.4% more capacity in the absorption chiller, a 1.46% higher EUF, and a 1.04% rise in the PES - comparing cases 3 and 8.

ARI 560-92 defined a methodology to test and evaluate absorption chiller performance. A single effect absorption chiller was tested with low pressure steam. A hot water absorption chiller had a nominal capacity associated with their steam test capacity, which means that the hot water absorption chiller was able to produce a higher capacity if steam or a higher temperature hot water was used. Today absorption chillers are being manufactured as a more customized machine. Ask your absorption chiller supplier to select an absorption chiller able to operate with higher temperature input hot water (jacket water reheat). Design your cooling tower system to the absorption chiller higher capacity.

The scenario used for comparison in this study can be intended as a high-efficiency scenario: (i) thermal plant efficiency is 45% assuming grid losses, (i) hot water, and steam are produced with 92% efficiency and (ii) mid-size electrical chillers has a 4.2 COP (0.8 kW/RT). Most of the countries and real installations face a less efficient scenario. But even at this high-efficiency scenario an 18% primary energy savings (CO_2 emission reduction) is predicted.

COGMCI developers suggest customers, policymakers, stakeholders, and the engineering team evaluate the possibilities and take the final decision based on their main goals. A good solution certainly must have high individual performance indicators, achieve the project's main goals with an attractive payback period.

From the environmental point of view, the PES (annex I) analysis reveals the site CHP potential to save energy and reduce CO_2 emissions. Better technical solution does not coincide with the lower payback solution. Incentives to high primary energy savings and fare rules for exported electricity can contribute to approximate both.

The results revealed that oversized engine systems can (i) work as a demand response system, (ii) save more primary energy, and (iii) can export electricity to the grid a. Basic planned systems are limiting the project energy savings and CO_2 emissions reduction. COGMCI can help you design and size your engine CHP system.

Cases 5 to 8 are formed by the same engine and CHP equipment with different operational modes. The results reveal the flexibility of engine CHP systems, allowing a system to operate at full load exporting electricity to the grid (case 8), at electrical dispatch providing almost the total site electricity needs (case 5) or at a high efficiency defined EUF at thermal dispatch (cases 6 and 7). Engine CHP system can adjust their operation mode to the intermittence of renewable production (solar and wind).

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ANNEX I – EQUIVALENT THERMAL EFFICIENCY CALCULATION

$$EUF = \frac{\dot{W}_{net}+\dot{m}_{14}(h_{15}-h_{14})+\dot{m}_{12}(h_{13}-h_{12})+\dot{m}_{16}(h_{16}-h_{17})}{\dot{m}_{1}.h_{1}} \quad [1]$$

$$\dot{E}c = \dot{E}_{hw1} + \dot{E}_{hw2} + \dot{E}_{st} + \dot{E}_{elet} \quad [2]$$

$$PEC_{without} = \frac{\dot{E}_{hw1}}{\eta_{hw1}} + \frac{\dot{E}_{hw2}}{\eta_{hw2}} + \frac{\dot{E}_{st}}{\eta_{st}} + \frac{\dot{E}_{elet}}{\eta_{elet}} \quad [3]$$

$$\dot{E}_{hw1s} = \dot{E}_{hw1} - \dot{E}_{hw1T} \quad [4]$$

$$\dot{E}_{hw2s} = \dot{E}_{hw2} - \dot{E}_{hw2T} \quad [5]$$

$$\dot{E}_{sts} = \dot{E}_{st} - \dot{E}_{stT} \quad [6]$$

$$\dot{E}_{elets} = \dot{E}_{elet} - \dot{E}_{eletav} - E_{eletT} \quad [7]$$

$$\dot{E}_{eletav} = \dot{E}_{cwT}/COP \quad [8]$$

Trigeneration energy consumption can be calculated as:

$$\dot{E}_{trig} = \dot{E}_{hw1T} + \dot{E}_{hw2T} + \dot{E}_{stT} + \dot{E}_{cwT} + \dot{E}_{eletT} + \dot{E}_{losses} \quad [9]$$

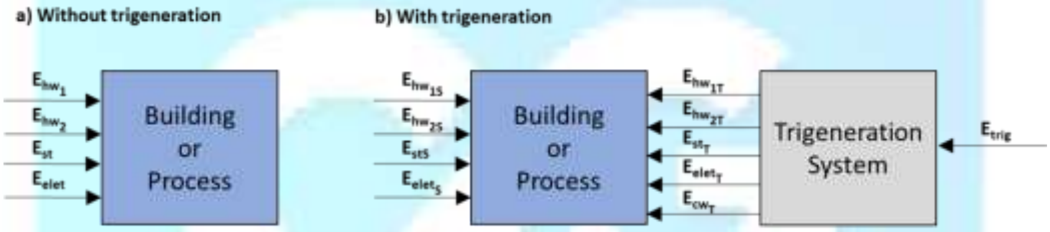

Figure 13 – building/process energy consumption

$$PEC_{withTrig} = \frac{\dot{E}_{hw1s}}{\eta_{hw1s}} + \frac{\dot{E}_{hw2s}}{\eta_{hw2s}} + \frac{\dot{E}_{sts}}{\eta_{sts}} + \frac{\dot{E}_{elets}}{\eta_{elets}} + \dot{E}_{trig} \quad [10]$$

$$PEC_{without} = PEC_{withTrig} \quad [11]$$

$$\frac{\dot{E}_{hw1}}{\eta_{hw1}} + \frac{\dot{E}_{hw2}}{\eta_{hw2}} + \frac{\dot{E}_{st}}{\eta_{st}} + \frac{\dot{E}_{elet}}{\eta_{elet}} = \frac{\dot{E}_{hw1s}}{\eta_{hw1s}} + \frac{\dot{E}_{hw2s}}{\eta_{hw2s}} + \frac{\dot{E}_{sts}}{\eta_{sts}} + \frac{\dot{E}_{elets}}{\eta_{elets}} + \dot{E}_{trig} \quad [12]$$

$$\frac{\dot{E}_{hw1}-\dot{E}_{hw1s}}{\eta_{hw1}} + \frac{\dot{E}_{hw2}-\dot{E}_{hw2s}}{\eta_{hw2}} + \frac{\dot{E}_{st}-\dot{E}_{sts}}{\eta_{st}} + \frac{\dot{E}_{elet}-\dot{E}_{elets}}{\eta_{elet}} = \dot{E}_{trig} \quad [13]$$

$$\eta_{elet} = \frac{\dot{E}_{elet}-\dot{E}_{elets}}{\dot{E}_{trig}-\left(\frac{\dot{E}_{hw1}-\dot{E}_{hw1s}}{\eta_{hw1}}+\frac{\dot{E}_{hw2}-\dot{E}_{hw2s}}{\eta_{hw2}}+\frac{\dot{E}_{st}-\dot{E}_{sts}}{\eta_{st}}\right)} = ETE \quad [14]$$

$$\eta_{elet} = \frac{\frac{\dot{E}_{elet}-\dot{E}_{elets}}{F_{gridloss}}}{\dot{E}_{trig}-\left(\frac{\dot{E}_{hw}-\dot{E}_{hws}}{\eta_{hw}}+\frac{\dot{E}_{st}-\dot{E}_{sts}}{\eta_{st}}\right)} = ETE_{GL} \quad [15]$$

$$PES\ (\%) = \left(\frac{PEC_{without} - PEC_{withTrig}}{PEC_{without}}\right).100 \quad [16]$$

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ANNEX II – PES – EU DIRECTIVE

$$PES_{AnnexII} = \left(1 - \frac{1}{\frac{\eta_{CHP\ Heat}}{\eta_{refHeat}} + \frac{\eta_{CHP\ elets}}{\eta_{refelet}}}\right).100\% \qquad [17]$$

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ANNEX I

Harmonized efficiency reference values for separate production of electricity

(referred to in Article 1)

In the table below the harmonized efficiency reference values for separate production of electricity ... calorific value and standard atmospheric ISO conditions (15 °C ambient temperature, 1,013 b... humidity).

Category		Type of fuel	Year of c... Before 2012	20...
Solids	S1	Hard coal including anthracite, bituminous coal, sub-bituminous coal, coke, semi-coke, pet coke	44,2	4
	S2	Lignite, lignite briquettes, shale oil	41,8	4
	S3	Peat, peat briquettes	39,0	3
	S4	Dry biomass including wood and other solid biomass including wood pellets and briquettes, dried woodchips, clean and dry waste wood, nut shells and olive and other stones	33,0	3
	S5	Other solid biomass including all wood not included under S4 and black and brown liquor	25,0	2
	S6	Municipal and industrial waste (non-renewable) and renewable/bio-degradable waste	25,0	2
Liquids	L7	Heavy fuel oil, gas/diesel oil, other oil products	44,2	4
	L8	Bio-liquids including bio-methanol, bioethanol, bio-butanol, biodiesel and other bio-liquids	44,2	4
	L9	Waste liquids including biodegradable and non-renewable waste (including tallow, fat and spent grain)	25,0	2
Gaseous	G10	Natural gas, LPG, LNG and biomethane	52,5	5
	G11	Refinery gases hydrogen and synthetic gas	44,2	4
	G12	Biogas produced from anaerobic digestion, landfill, and sewage treatment	42,0	4
	G13	Coke oven gas, blast furnace gas, mining gas, and other recovered gases (excluding refinery gas)	35,0	3
Other	O14	Waste heat (including high temperature process exhaust gases, product from exothermic chemical reactions)		
	O15	Nuclear		
	O16	Solar thermal		
	O17	Geothermal		
	O18	Other fuels not mentioned above		

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ANNEX II

Harmonized efficiency reference values for separate production of heat

(referred to in Article 1)

In the table below the harmonized efficiency reference values for separate production of heat are based on net calorific value and standard atmospheric ISO conditions (15 °C ambient temperature, 1,013 bar, 60 % relative humidity).

Category		Type of fuel	Year of construction: Before 2016			From 2016		
			Hot water	Steam (*)	Direct use of exhaust gases (**)	Hot water	Steam (*)	Direct use of exhaust gases (**)
Solids	S1	Hard coal including anthracite, bituminous coal, sub-bituminous coal, coke, semi-coke, pet coke	88	83	80	88	83	80
	S2	Lignite, lignite briquettes, shale oil	86	81	78	86	81	78
	S3	Peat, peat briquettes	86	81	78	86	81	78
	S4	Dry biomass including wood and other solid biomass including wood pellets and briquettes, dried woodchips, clean and dry waste wood, nut shells and olive and other stones	86	81	78	86	81	78
	S5	Other solid biomass including all wood not included under S4 and black and brown liquor.	80	75	72	80	75	72
	S6	Municipal and industrial waste (non-renewable) and renewable/bio-degradable waste	80	75	72	80	75	72
Liquids	L7	Heavy fuel oil, gas/diesel oil, other oil products	89	84	81	85	80	77
	L8	Bio-liquids including bio-methanol, bioethanol, bio-butanol, biodiesel and other bio-liquids	89	84	81	85	80	77
	L9	Waste liquids including biodegradable and non-renewable waste (including tallow, fat and spent grain).	80	75	72	75	70	67
Gaseous	G10	Natural gas, LPG, LNG and biomethane	90	85	82	92	87	84
	G11	Refinery gases hydrogen and synthesis gas	89	84	81	90	85	82
	G12	Biogas produced from anaerobic digestion, landfill, and sewage treatment	70	65	62	80	75	72
	G13	Coke oven gas, blast furnace gas, mining gas, and other recovered gases (excluding refinery gas)	80	75	72	80	75	72

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ANNEX IV

Correction factors for avoided grid losses for the application of the harmonized efficiency reference values for separate production of electricity

(referred to in Article 2(2))

Connection voltage level	Correction factor (Off-site)	Correction factor (On-site)
≥ 345 kV	1	0,976
≥ 200 - < 345 kV	0,972	0,963
≥ 100 - < 200 kV	0,963	0,951
≥ 50 - < 100 kV	0,952	0,936
≥ 12 - < 50 kV	0,935	0,914
≥ 0,45 - < 12kV	0,918	0,891
< 0,45 kV	0,888	0,851

Example:

A 100 kWel cogeneration unit with a reciprocating engine driven with natural gas generates electricity at 380 V. Of this, 85 % is used for own consumption and 15 % is fed into the grid. The plant was constructed in 2010. The annual ambient temperature is 15 °C (so no climatic correction is necessary).

After the grid loss correction the resulting efficiency reference value for the separate production of electricity in this cogeneration unit would be (based on the weighted mean of the factors in this Annex):

Ref Eη = 52,5 % × (0,851 × 85 % + 0,888 × 15 %) = 45,0 %

NOMENCLATURE

RT	refrigeration tons
COP	coefficient of performance – electrical and absorption chillers.
E_c	energy consumption (kWh)
E_{hw1}	hot water energy consumption - medium temperature (kWh)
E_{hw2}	hot water energy consumption - low temperature (kWh)
E_{hw1s}	complementary hot water energy consumption – medium temperature (kWh)
E_{hw2s}	complementary hot water energy consumption – low temperature (kWh)
E_{hw1T}	trigeneration hot water energy production - medium temperature (kWh)
E_{hw2T}	trigeneration hot water energy production - low temperature (kWh)
E_{st}	steam energy consumption (kWh)
E_{sts}	complementary steam energy consumption (kWh)
E_{stT}	trigeneration steam energy production (kWh)
E_{elet}	electricity consumption (kWh)
E_{eletav}	avoided electricity consumption (kWh)
E_{elets}	complementary 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)
PES	Primary Energy Savings (kW.h)
η_{hw}	hot water production efficiency
η_{st}	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)
h	enthalpy (kJ/kg)
η	efficiency
$\eta_{CHPHeat}$	heat efficiency of cogeneration production - defined as annual useful heat output divided by the fuel input used to produce the sum of useful heat and electricity from cogeneration
$\eta_{refHeat}$	efficiency reference value for separate heat production.
$\eta_{CHPelets}$	electrical efficiency of the cogeneration production - defined as annual electricity from cogeneration divided by the fuel input used to produce the sum of useful heat output and electricity from cogeneration.
$\eta_{Refelet}$	efficiency reference value for separate electricity production.

Subscripts

1 to 20	state points in the trigeneration scheme
hot wat	hot water
chilled wat	chilled water
elet	electricity

Abbreviations

SC	secondary circuit
PC	primary circuit
EGHE	exhaust gas heat exchanger
HE	heat exchanger
CHP	combined cooling and heating power

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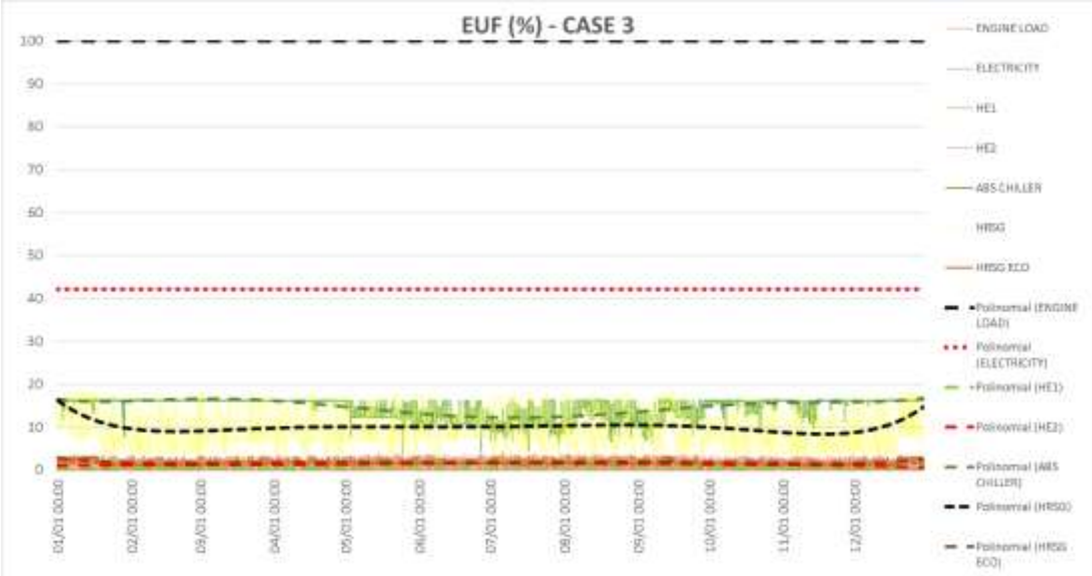
ANNEX 3 – EUF


EUF (%) - CASE 3
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80
70
60
50
40
30
20
10
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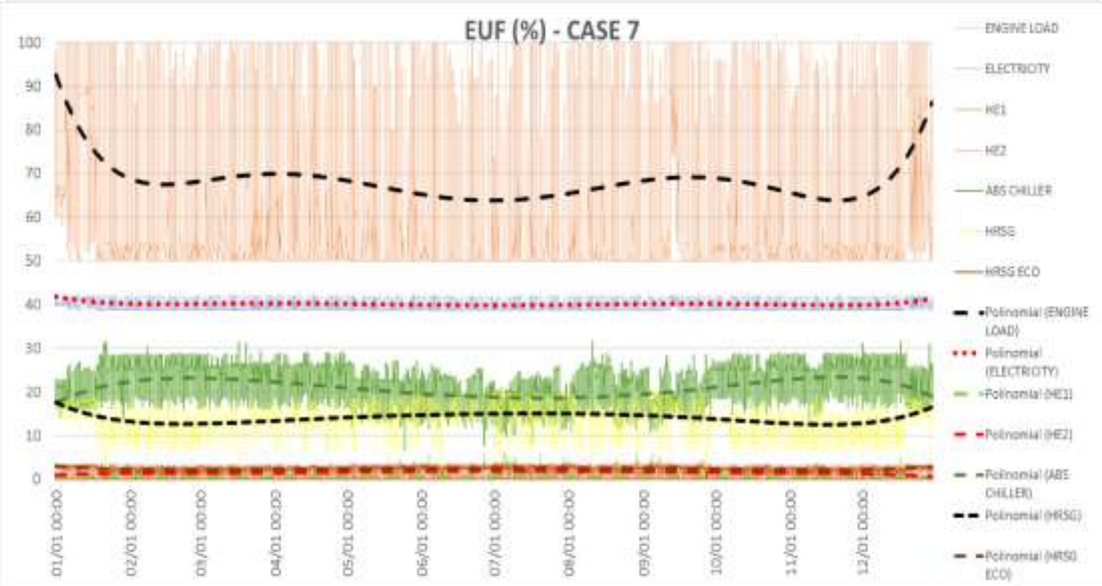
02/01 00:00
03/01 00:00
04/01 00:00
05/01 00:00
06/01 00:00
07/01 00:00
08/01 00:00
09/01 00:00
10/01 00:00
11/01 00:00
12/01 00:00
ENGINE LOAD
ELECTRICITY
HE1
HE2
ABS CHILLER
HRSG
HRSG ECO
Polinomial (ENGINE LOAD)
Polinomial (ELECTRICITY)
Polinomial (HE1)
Polinomial (HE2)
Polinomial (ABS CHILLER)
Polinomial (HRSG)
Polinomial (HRSG ECO)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40
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20
10
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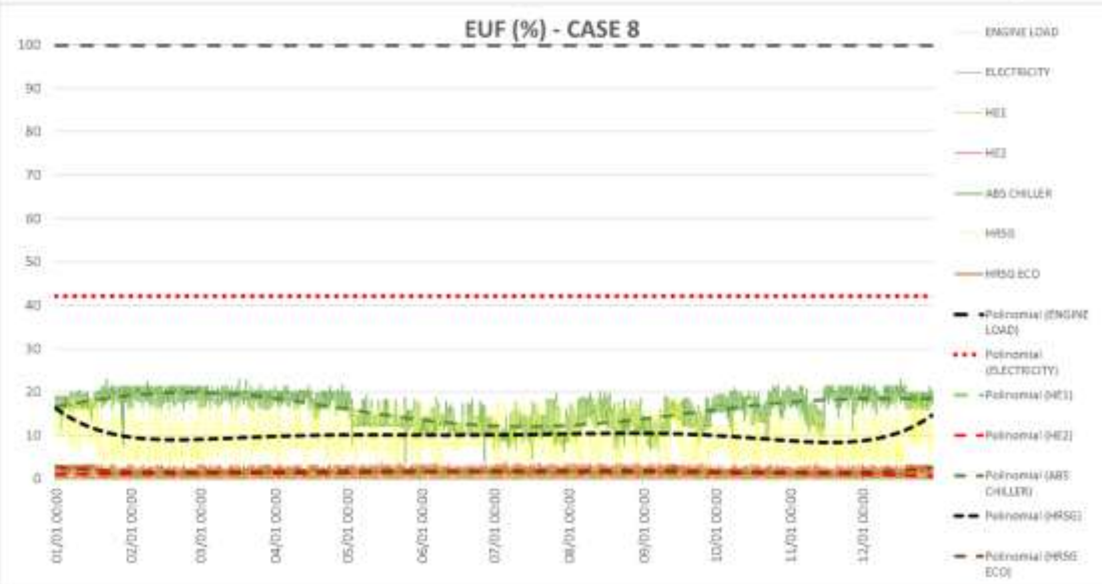
06/01 00:00
07/01 00:00
08/01 00:00
09/01 00:00
10/01 00:00
11/01 00:00
12/01 00:00
ENGINE LOAD
ELECTRICITY
HE1
HE2
ABS CHILLER
HRSG
HRSG ECO
Polinomial (ENGINE LOAD)
Polinomial (ELECTRICITY)
Polinomial (HE1)
Polinomial (HE2)
Polinomial (ABS CHILLER)
Polinomial (HRSG)
Polinomial (HRSG ECO)


EUF (%) - CASE 8
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70
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40
30
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10
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05/01 00:00
06/01 00:00
07/01 00:00
08/01 00:00
09/01 00:00
10/01 00:00
11/01 00:00
12/01 00:00
ENGINE LOAD
ELECTRICITY
HE1
HE2
ABS CHILLER
HRSG
HRSG ECO
Polinomial (ENGINE LOAD)
Polinomial (ELECTRICITY)
Polinomial (HE1)
Polinomial (HE2)
Polinomial (ABS CHILLER)
Polinomial (HRSG)
Polinomial (HRSG ECO)