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GETTING THE MOST FROM A CHP DESIGN & ANALYSIS

ENGINEERS NEWSLETTER - 03

COMPARING CHP ENGINE OPERATIONAL STRATEGIES: FULL LOAD, ELETRICAL DISPATCH AND THERMAL DISPATCH – SUMMER

Aim: at this COGMCI Engineer's Newsletter the COGMCI software is used to evaluate different operational strategies of a defined CHP engine system attending 24 hour energy loads of a typical summer day (electricity, hot water and chilled water – air conditioning).

The proposed engine is oversized, suitable for exporting electricity to the grid for most of day.

Five different operational modes are evaluated:

Case 1 - Engine at full load;

Case 2 - Engine operating at electrical dispatch;

Case 3 - Engine operating at thermal dispatch – EUF = 65%;

Case 4 - Engine operating at thermal dispatch – EUF = 70%;

Case 5 - Engine operating at thermal dispatch – EUF = 75%;

EUF - Energy Utilization Factor.

1. The energy demands

Energy demands of a typical summer day are used in the analysis. Figure 1 reveals the electricity demand, figure 2 the cooling load or chilled water demand – air conditioning, figure 3 refers to hot water demand for sanitary use and figure 4 shows the local dry bulb temperature (°C) and relative humidity (%).

Without an engine trigeneration system the electricity is bought from the grid, the cooling load is met by electrical chillers with a COP equal to 4.4 and the hot water for sanitary use is provided by fueled boilers with 80% efficiency.

Electrical chiller consumption is already computed in figure 1.

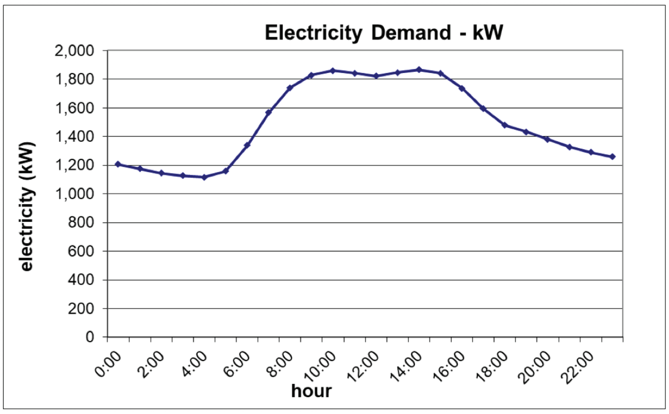

Figure 1 – Electricity demand

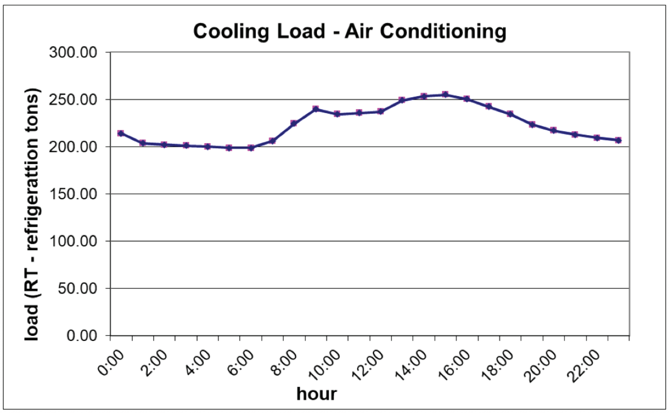

Figure 2 – Cooling load

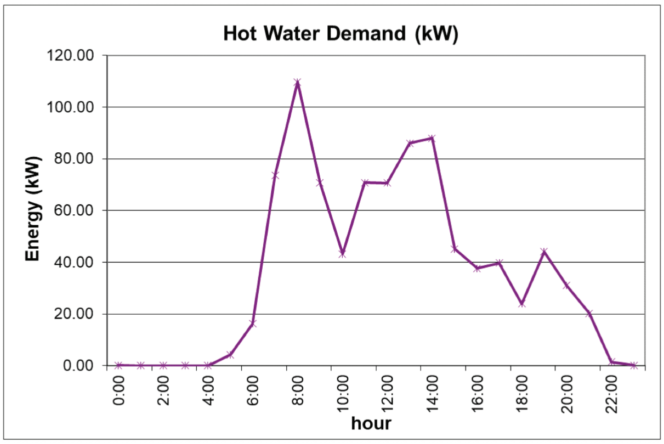

Figure 3 – hot water demand (sanitary use)

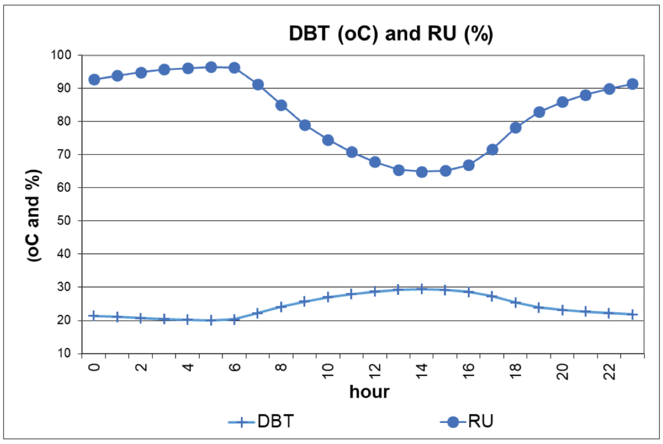

Figure 4 – dry bulb temperature and relative humidity

2. Trigeneration scheme

The trigeneration scheme simulated in this study is shown in figure 5.

The hot water from the primary circuit (PC) (jacket water) leaving the engine heat exchanger [flow 2] passes through an exhaust gas heat exchanger (EGHE) and is warmed [flow 3] before entering the hot water driven single effect absorption chiller. After leaving the absorption chiller [flow 4] the PC flow passes through HE1 [flows 4-5] warming the hot water for sanitary use [flows 14-15] that has already passed through HE2 [flows 12-13].

The energy from the secondary circuit (SC) (engine intercooler) [flows 8-11] is recovered at HE2 [flows 12-13] to warm the hot water for sanitary use. HE2 and HE1 are arranged in series [flows 12 to 15].

The hot water demand for sanitary use is shown in figure 3. The hot water demand for sanitary use is warmed from 22.2ºC to 43ºC by recovering energy from both the PC (HE1) and SC (HE2).

The EGHE is designed to provide energy to the PC flow leaving the engine [flow 2]. It is designed to achieve an approach point of 16.6ºC [flow 20 temperature – flow 2 temperature].

The hot water absorption chiller is selected to recover energy from the engine [flow 3-4] and produce chilled water at 7.2ºC with the cooling water entering the condenser at 29ºC. A COP equal to 0.8 is defined for the single effect hot water absorption chiller.

Main design parameters:

- Engine data utilized in this study is shown in table 1.
- Hot water single effect absorption chiller COP is defined as 0.8.
- HE2 design data are from 22.2ºC to 43ºC
- HE1 design data are from 30ºC to 43ºC
- HE2 and HE1 are arranged in series.
- EGHE has an approach point of 16.6ºC.
- Engine temperatures are as recommended by the manufacturer.
- Absorption chiller produces chilled water from 13.3 to 7.2ºC.
- Parasitic load is 2% of the total engine power.

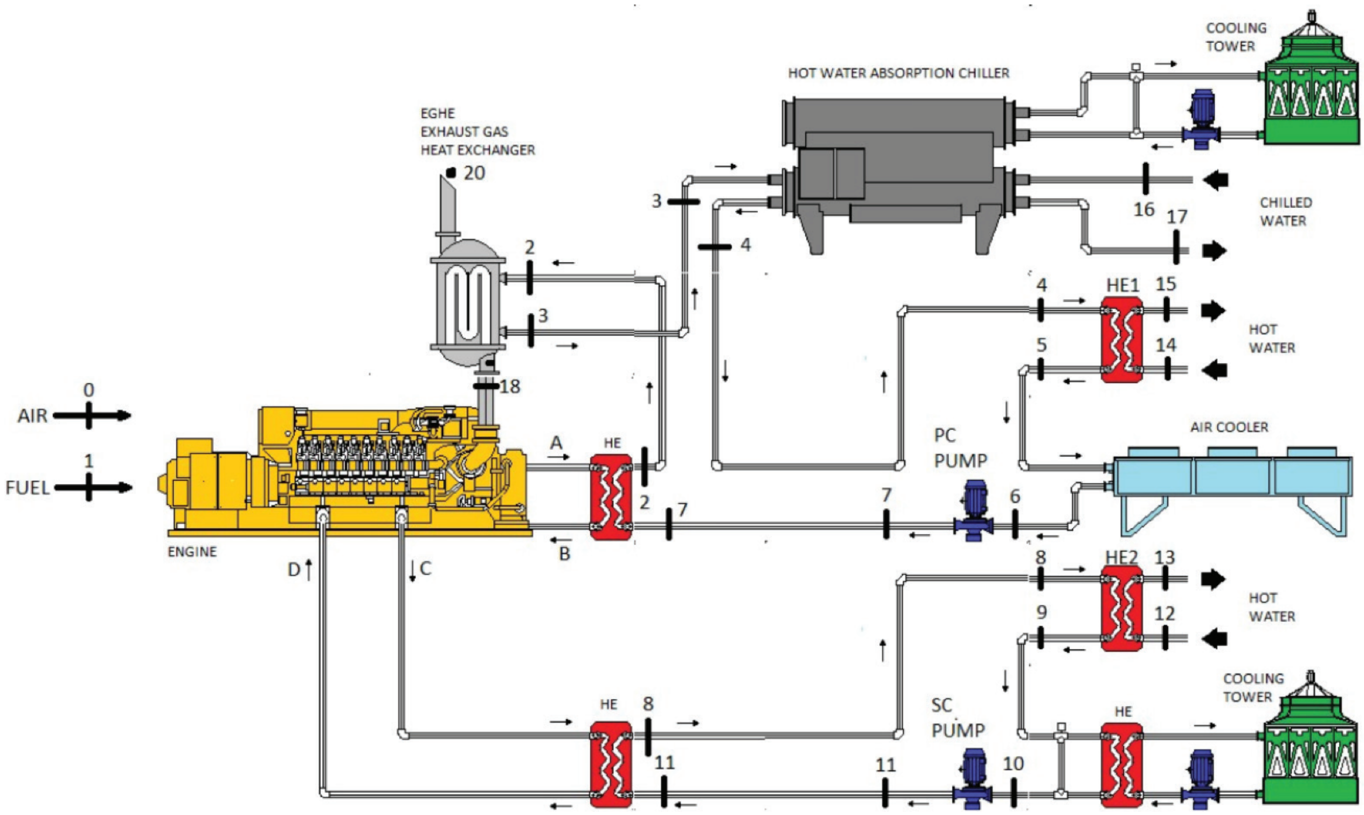

Figure 5 – the trigeneration scheme

The engine performance data utilized in this analysis is shown in table 1. The data was obtained from an engine manufacturer. Figure 6 shows the engine part load performance. The part load performance curves (energy balance and the exhaust gas flow and temperature) were built using polynomial regression and inserted in the software. The engine net power production is 2% lower than the nominal power to account for the system parasitic load (pumps, fans, etc.).

Table 1 – engine data

	Engine 1
Model	CG170-16
Engine power (kW)	1560
Primary circuit energy (kW)	804
Secondary circuit energy (kW)	144
Exhaust gas energy (kW)	1013
Exhaus gas flow (kg/h)	8589
Exhaust gas temperature (°C)	420
PC water entering/leaving (°C)	80 / 93
SC water entering/leaving (°C)	40 / 44
Electrical efficiency (%)	43

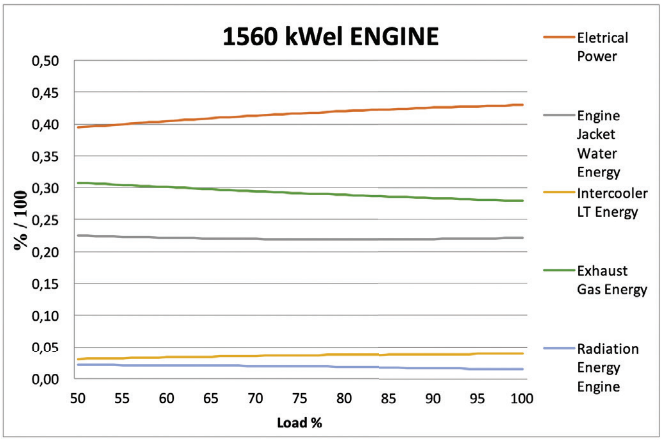

Figure 6 – engine energy balance

Table 2 – thermodynamic data

Table 2 shows the engine cog/trig system thermodynamic data in the design conditions. Design conditions assume the engine operating at full load. Table 3 shows the energy in the cog/trig outputs (electricity, hot water and chilled water).

An EUF (energy utilization factor) equal to 81.93% and an exergy efficiency of 38.45% are calculated, assuming that all engine trigeneration outputs are being utilized.

flow number	pressure (kPa)	temperature (oC)	mass flow (kg/s)	enthalpy (kJ/kg)	entropy (kJ/kg.K)
0	100.000	25.000	2.306	298.800	5.699
1	100.000	25.000	0.080	45,461.995	0.000
2	462.500	93.000	14.680	389.867	1.227
3	375.000	105.935	14.680	444.313	1.373
4	287.500	81.093	14.680	339.700	1.088
5	200.000	80.000	14.680	335.042	1.075
6	200.000	80.000	14.680	335.042	1.075
7	550.000	80.000	14.680	335.324	1.075
8	275.000	44.000	8.683	184.408	0.625
9	150.000	40.000	8.683	167.582	0.572
10	150.000	40.000	8.683	167.582	0.572
11	400.000	40.000	8.683	167.806	0.572
12	300.000	22.222	2.447	93.437	0.328
13	250.000	36.414	2.447	152.689	0.524
14	250.000	36.414	2.447	152.689	0.524
15	200.000	43.000	2.447	180.163	0.612
16	400.000	13.333	47.885	56.352	0.200
17	300.000	7.222	47.885	30.640	0.110
18	102.000	420.000	2.386	735.584	7.739
19	102.000	420.000	2.386	735.584	7.739
20	100.000	109.667	2.386	397.931	7.096

Table 3 – electricity, chilled water and hot water

	ENERGY		EXERGY	
	(kW)	(%)	(kW)	(%)
hot water SC	144.990	4.00	1.993	0.05
hot water PC	67.229	1.85	3.026	0.07
chilled water	1231.219	33.94	53.703	1.30
steam	0	0.00	0	0.00
power	1,529	42.14	1,529	37.03
SUM	2972.2376	81.93	1587.5228	38.45

3. Simulated results

Case 1 – Full load

At full engine load the cog/trig system is able to produce electricity, hot water and chilled water at the quantities shown at table 3.

Comparing figure 1 (electricity demand) with the nominal engine power we see that cog/trig system is able to export electricity to the grid at most times of the day. The cog/trig system absorption chiller reduces the site electricity consumption, since it produces chilled water using engine residual energy instead of the consuming electricity in electrical chillers. Figure 1 electricity demand curve will be lower due to the absorption chiller use.

The hot water energy demand is between 0 and 110 kW with a demand temperature of 43ºC. The SC can attend this demand since 144 kW are available (table 3) with a temperature of 44ºC (flow 8).

Table 3 reveals that the cog/trig system produces 1,231.2 kW (349.8 RT) of chilled water. The cooling load profile of this study (figure 2) is between 200 and 255 RT, it means that the absorption chiller of the cog/trig system operating at full load attends the peak cooling load. In fact the absorption chiller will always operate at part load in this typical load curve.

Figure 7 shows the main results of case 1. The engine load is always 1 (full load) and electricity production contributes 42.1% to the EUF. The absorption chiller contributes between 19.2 and 25.2% and hot water contributes between 0 and 3%. A final EUF between 61.5 and 69.7% was calculated. Average engine load is 100% (full engine load).

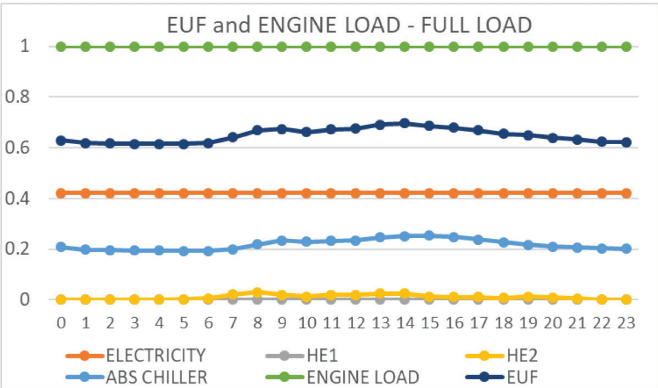

Figure 7 – EUF and engine load – case 1

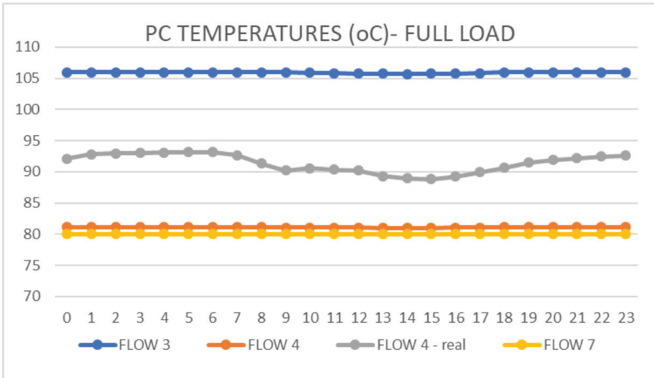

Figure 8 – PC hot water temperatures – case 1

Figure 8 shows the PC hot water temperatures. Flow 3 is entering the absorption chiller. Flow 4 temperature is the predicted PC water temperature leaving the absorption chiller if the absorption chiller is operating at full load. Flow 4 – real shows the real flow temperature leaving the absorption chiller assuming the absorption chiller runs at part load – attending the cooling load profile (figure 2). Flow 7 is the PC temperature returning to the engine. It can be noted that a significant fraction of the PC energy is not used and needs to be rejected (Flow 4 real – Flow 7). A close to 25ºC temperature difference would be verified at the absorption chiller (flow 3 temperature – flow 4 temperature) if the abs chiller was operating at full load. Since a fraction of the hot water flow by-passes it, a real temperature difference of 12.8-16.9ºC is verified (flow 3 temperature – flow 4 real temperature).

Case 2 – Electrical dispatch

Operating at electrical dispatch the engine follows the site electrical demand curve.

Figure 9 shows that the engine operates at full load between 9:00 a.m. to 5:00 p.m. and at part load in the remaining hours.

At part engine load more thermal energy is available in the exhaust gases and therefore in the PC (see figure 6). The absorption chiller part load performance is up to 10% more efficient then at full load (COP). At part engine load more thermal energy is used by the absorption chiller. Due to these factors a higher participation of the chilled water in the hourly EUF is verified.

Figure 9 shows that electricity contributes between 39.9 and 42.1%, chilled water between 21.6 and 29.3% and hot water between 0 and 3%. Final EUF is between 65.6 and 69.7%. Average engine load is 83.4%.

Figure 10 shows that the temperature difference in the absorption chiller (flow 3 – flow 4 real) is almost constant and less PC energy is rejected when compared to case 1 (figure 8). The absorption chiller operates at part load all the time with a temperature difference between 14-17ºC (flow 3 temperature – flow 4-real temperature).

Due to part engine load, hot water energy demand is not totally met by HE2 and HE1 is also used.

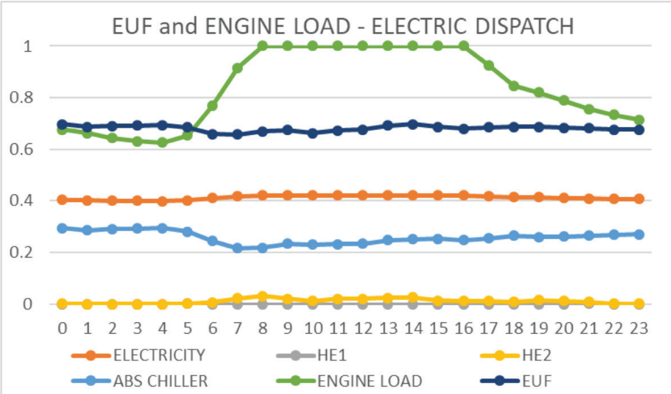

Figure 9 – EUF and engine load – case 2

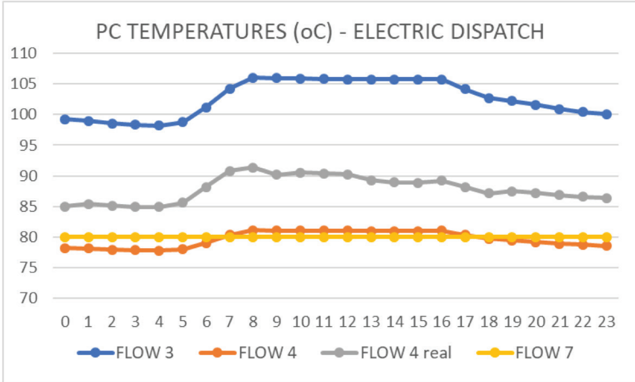

Figure 10 – PC hot water temperatures – case 2

Defining Thermal Dispatch mode

Operating at thermal dispatch the engine follows a thermal demand curve. Cog/trig systems can attend more than one thermal load (steam, hot water, chilled water). Thermal dispatch mode simulated by the COGMCI Software is defined by a minimal acceptable EUF, the higher engine load that achieve an EUF above the defined thermal dispatch EUF will be the defined engine load. The engine lower load limit is 50%.

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

E_{hw} – hot water energy (kW)
E_{cw} – chilled water energy (kW)
W_{net} – net electricity production (kW)
LHV – fuel lower heating value (kW)
m_{fuel} – fuel mass flow (kg/s)

Case 3 – Thermal dispatch – EUF=65%

In the thermal dispatch mode the engine cog/trig system should maintain a minimal EUF, defined in case 3 as 65%.

Figure 11 shows that the engine operates at full load between 9:00 a.m and 7:00 p.m and at part load in the remaining hours. Electricity contributes between 41.1 and 42.1%, chilled water between 21.1 and 25.3% and hot water between 0 and 3%. Final EUF is between 65.1 and 69.7%. Average engine load is 91.6%.

Figure 12 shows that the temperature difference in the absorption chiller (flow 3 – flow 4 real) is between 13-17°C.

Hot water energy demand is totally met by HE2 (SC energy).

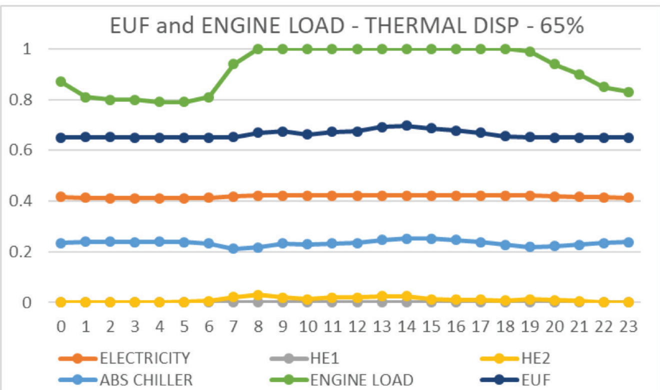

Figure 11 – EUF and engine load – case 3

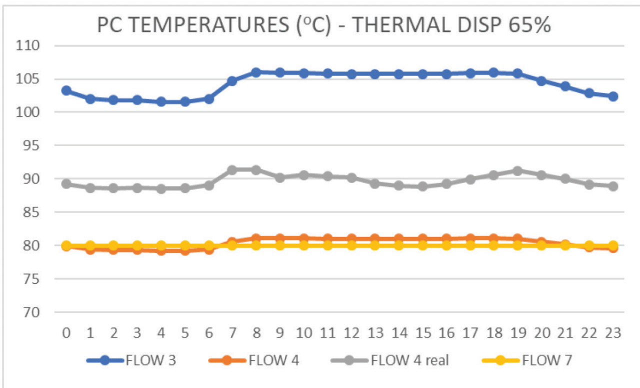

Figure 12 – PC hot water temperatures – case 3

Case 4 – Thermal dispatch – EUF=70%

Figure 13 shows that the engine operates at part load all day long. Electricity contributes between 39.6 and 42.1%, chilled water between 25.2 and 30.6% and hot water between 0 and 3.5%. Final EUF is very close to 70%. Average engine load is 75.1%.

Figure 14 shows that the temperature difference in the absorption chiller (flow 3 temperature – flow 4 real temperature) is between 13-17ºC.

Hot water energy demand is not totally met by HE2 and HE1 is also used.

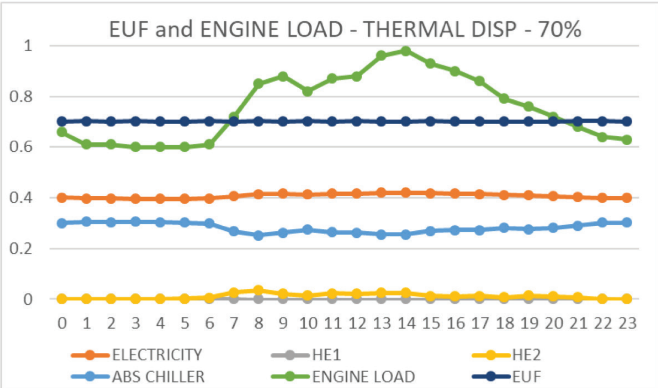

Figure 13 – EUF and engine load – case 4

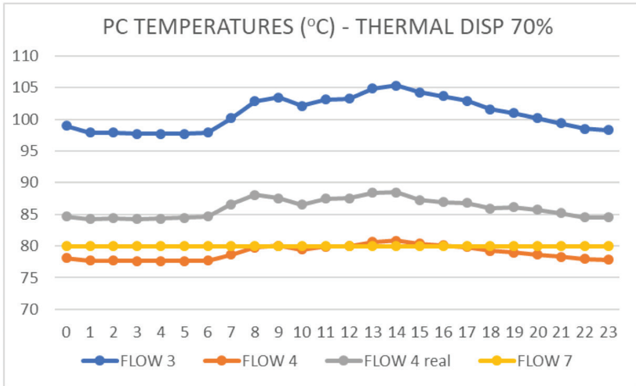

Figure 14 – PC hot water temperatures – case 4

Case 5 – Thermal dispatch – EUF=75%

Figure 15 reveals that engine operates at part load all day. Electricity contributes between 38.7 and 41.1%, chilled water between 30.6 and 36.8% and hot water between 0 and 4.3%. Final EUF is very close to 75%. Average engine load is 60.5%, note that between hours 1 to 6 and hour 23 the engine load is limited to 50% even if the EUF is lower than 75%.

Figure 16 reveals the temperature difference in the absorption chiller as between 13.4-17.4ºC (Flow 3 temperature – Flow 4 real temperature).

Hot water energy demand is not totally attended by HE2 and HE1 is also used.

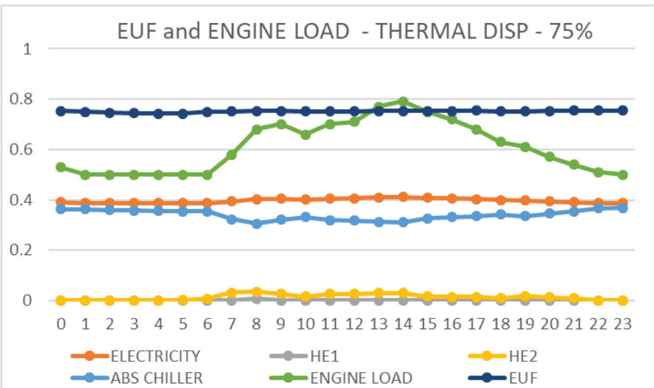

Figure 15 – EUF and engine load – case 5

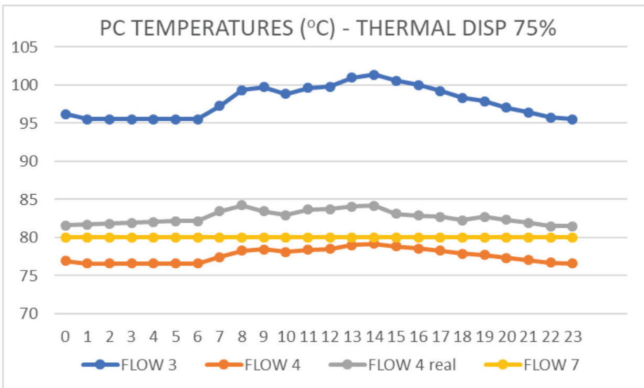

Figure 16 – PC hot water temperatures – case 5

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Table 4 - Results Summary

		CASE 1	CASE 2	CASE 3	CASE 4	CASE 5
		FULL LOAD	ELECTRICAL DISPATCH	THERMAL DISP EUF=65%	THERMAL DISP EUF=70%	THERMAL DISP EUF=75%
1	Power consumption (kWh/day)	35970.10	35970.10	35970.10	35970.10	35970.10
2	Power consumption corrected (kWh/day)	31687.94	31687.94	31687.94	31687.94	31687.94
3	NET Power produced (kWh/day)	36470.46	30609.13	33596.32	27562.32	22205.17
4	Surplus electricity (kWh/day)	-4782.52	1078.81	-1908.38	4125.62	9482.77
5	Cooling load (RT/day)	5352.70	5352.70	5352.70	5352.70	5352.70
6	Ab.chiller production (RT/day)	5352.70	5352.70	5352.70	5352.70	5352.70
7	cooling load complementary (RT/day)	0.00	0.00	0.00	0.00	0.00
8	Avoided electricity abs.chiller (kWh/day)	4282.16	4282.16	4282.16	4282.16	4282.16
9	HW demand (kWh/day)	876.66	876.66	876.66	876.66	876.66
10	HE1 production (kWh/day)	0.00	0.41	0.00	3.45	39.68
11	HE2 production (kWh/day)	876.66	876.25	876.66	873.20	836.98
12	HW demand complementary (kWh/day)	0.00	0.00	0.00	0.00	0.00
13	Fuel flow energy (kWh/day)	86626.52	73963.80	80394.78	67389.48	55812.43
14	Thermal energy (kWh/day)	19718.17	19718.17	19718.17	19718.17	19718.17
15	EUF (%) - average	64.86	68.04	66.32	70.16	75.11
16	Thermal efficiency (%) - engine average	42.10	41.38	41.79	40.90	39.79
17	ENGINE LOAD (%) - average	100.00	83.42	91.57	75.12	60.52
18	CHILLED WATER % IN EUF - average	21.75	25.47	23.44	27.96	33.76
19	HOT WATER % IN EUF - average	1.01	1.19	1.09	1.30	1.57
	ETE - EQUIVALENT THERMAL EFFICIENCY (%)					
20	**ETE - no grid loss**	47.65	47.88	47.77	48.04	48.41
21	**ETE (10% GRID LOSS)**	52.94	53.20	53.07	53.37	53.79
22	**ETE (20% GRID LOSS)**	59.56	59.85	59.71	60.04	60.51

4. Discussion of results

Table 4 shows a summary of the main results.

Line 1 shows the daily electricity consumption calculated using figure 1. Line 2 shows the corrected daily electricity consumption assuming that the absorption chiller use will replace electricity consumption in the electrical chillers. Line 3 shows the engine net power production and line 4 the imported/exported daily electricity. It can be seen that cases 1 and 3 will export 4.78 and 1.91 MW.h/day respectively, while cases 2, 4 and 5 will import 1.08, 4.13 and 9.48 MW.h/day, respectively. Lines 5, 6 and 7 show the cooling load, the absorption chiller produced capacity and the necessary complementary chilled water capacity. Line 8 shows the avoided electricity consumption due to the absorption chiller use. Lines 9 to 11 show the hot water demand and production and line 12 shows the complementary hot water demand. Neither complementary chilled water (line 7) nor complementary hot water (line 12) are necessary.

Line 13 shows the engine fuel consumption and line 14 the engine´s recovered thermal energy.

EUF varies between 64.8% (case 1) and 75.11% (case 5) – line 15. Case 5 produces less electricity and showed the higher EUF, since more engine energy is recovered by the absorption chiller (line 18) and heat exchangers HE2 and HE1 (line 19), despite the lower engine thermal efficiency (line 16) due to a lower engine load (line 17).

In fact, at part engine load more residual energy is recovered for hot and chilled water production and a higher EUF is achieved.

The equivalent thermal efficiency (ETE) criteria is shown in lines 20-22. A high efficiency scenario for hot water production (80%) and chilled water production (COP=4.4) was defined. Neglecting electrical grid loss the ETE of the five cases are between 47.65 and 48.41% (line 20). In a 10% electrical grid loss the ETE scenario is between 52.94-53.79% (line 21) and in a 20% electrical grid loss scenario the ETE is between 59.56-60.51% (line 22). Graus et al studied some countries average thermal efficiency. Weighted average thermal efficiency (centralized natural gas thermal plants) when neglecting grid loss was shown to be 44% [1], electrical grid loss can be as high as 20%. Roseli et al [2] shown that in 2017 the average thermal efficiency assuming grid loss was 44.7% in Italy, despite a high quantity of high efficiency combined cycles.

5. Conclusions

The results were obtained by the COGMCI algorithm that joins engine, absorption chiller, HRSG, EGHE and heat exchangers being simulated outside design conditions (part load performance) with variable energy demands (electricity, chilled water and hot water) – [3].

In this study an oversized engine (able to export electricity to the grid) is simulated attending a typical summer day energy demand profile. Three different operational modes were evaluated (i) full load, (ii) electric dispatch and (iii) thermal dispatch. The thermal dispatch mode was evaluated at three different minimal EUF.

In the thermal dispatch mode with EUF of 70% and 75% less energy is rejected to the environment through the air cooler/cooling tower, see that the flow 4 real temperature is close to the flow 2 temperature in figures 14 and 16. A lower engine load reduces its thermal efficiency. The benefit of operating at thermal dispatch is that you can maintain a high efficiency operating condition (high EUF and ETE) while maintaining a "surplus" electricity production capacity. Surplus capacity can be used at peak grid times and/or at times of low production from renewable sources.

It possible for the engine cog/trig system to comply with rules for certified incentives (financial incentive) associated with the system efficiency.

In real systems thermal dispatch is not a usual solution, since (i) the engine load needs to be changed all the time to achieve the desired EUF (a PLC logic needs to be developed), (ii) without regulations cog/trig investors base their decisions on the payback period, part load operation usually increases the payback and (iii) a comprehensive tool like COGMCI needs to be used to show the possibilities of a cog/trig system at a potential site.

The best solution depends on the project goals. Lower payback projects compromise initial investment and energy savings while better solutions for a decarbonized electric strategy can lead to oversized systems able to export electricity to the grid. Higher capacity engine systems usually have a lower investment per installed kW.

In order to simplify the analysis developed in this study, demand curves of one day (24 hours) are utilized, but an analysis representing the different annual demands are recommended for better decisions – annual performance prediction. An annual analysis can show the cog/trig system performance and contribute to the selection of a high efficiency solution.

The analysis shows the flexibility of engine cog/trig systems, the same system design can operate at different operational strategies. Full load can be used in countries looking to increase their average thermal efficiency (centralized plants) and/or to expand their installed capacity. Electrical dispatch can be used in countries with no set fares for exporting electricity to the grid and/or countries looking for demand response projects. Thermal dispatch mode can be used by countries with a high share of intermittent renewables (solar and wind) participating in the electricity mix. Defining a high EUF leads to lower electricity production at times of high renewables production while reduced EUF can export electricity to the grid at times of low electricity production from intermittent renewables and/or peak grid hours.

In fact, several CHP systems can be connected to a city smart grid operating at different operational strategies according to the grid necessity, contributing to the grid stability while rising the country´s average thermal efficiency.

COGMCI software developers see cog/trig systems as an energy policy strategy able to contribute to the migration from fossil fuels to renewables, increasing countries average thermal efficiency, reducing CO_2 emissions, contributing to a stable electrical grid and could operate as a clean energy system when hydrogen is inserted in the natural gas network.

References

[1] Graus W H J, Vogt M and Worrell E, "International comparison of energy efficiency of fossil power generation". Energy Policy 35 (2007) 3936-3951.

[2] Roselli C., Marrasso E., Ssso M. and Tariello F., "Comparison of centralized and decentralized air conditioning systems for a multi-storey/multi users building integrated with electric and diesel vehicles and considering the evolution of the national energy system", Energy 2019 (177), 319-333.

[3] COGMCI SOFTWARE – www.sisterm.com.br/en/cogeneration

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