Sisterm
Thermal Systems

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GETTING THE MOST FROM A CHP DESIGN & ANALYSIS

ENGINEERS NEWSLETTER - 02

Comparing single and multiple engines COG/Trigeneration systems operating at electrical dispatch attending a typical day energy demands

At this COGMCI Engineer's Newsletter the COGMCI software is used to evaluate the benefit of multiple engines (two or three) against single engine cogeneration / trigeneration systems and discuss some of the influences that affect the results. To develop the analysis hypothetical demand curves are assumed (electricity, hot water and chilled water) – typical day. The cog/trig systems are simulated operating at electrical dispatch – engine produced electricity match the electricity demand.

At COGMCI when the engine CHP system is selected to operate at electrical dispatch, two and/or three engines share the electricity demand and operates at the same load. COGMCI software limits the engine load to 50%, since engines have their best performance at higher than 50% load. In multiple engines systems operating at electrical dispatch one engine is turned off if it loads is lower than 50% and turned on if the other engine load is 100%.

1. The energy demands – typical day

Figure 1 reveals the electricity demand profile, figure 2 the cooling load profile and figure 3 the hot water demand profile – the assumed curves represents a typical day.

In the electricity demand profile (figure 1) all the building and/or process electricity demand are included, even the electricity used at the electrical chillers to meet the cooling load (figure 2). The electrical chillers COP is assumed to be 3.5.

Sanitary use hot water demand (figure 3) is assumed to be attended by fueled boilers.

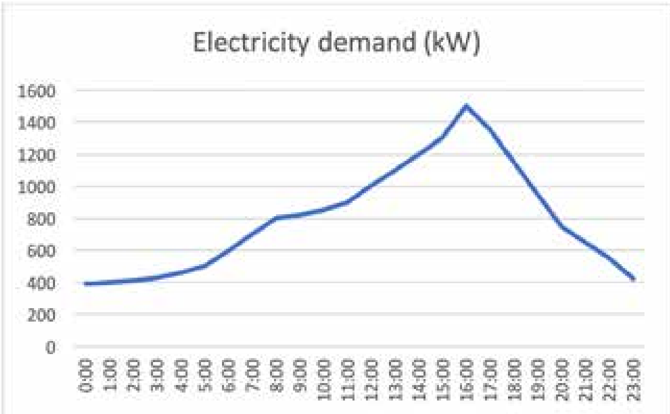

Figure 1 – Electricity demand

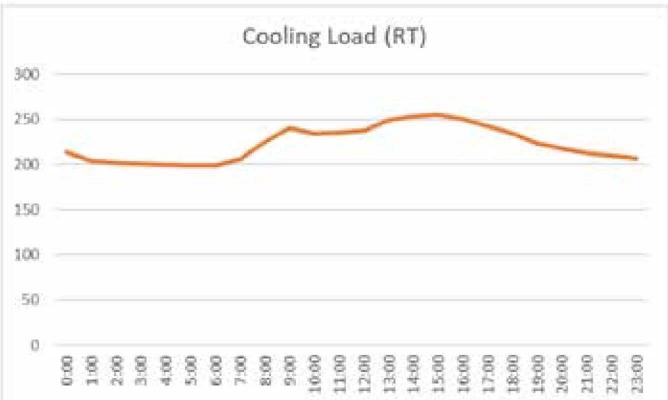

Figure 2 – Cooling load

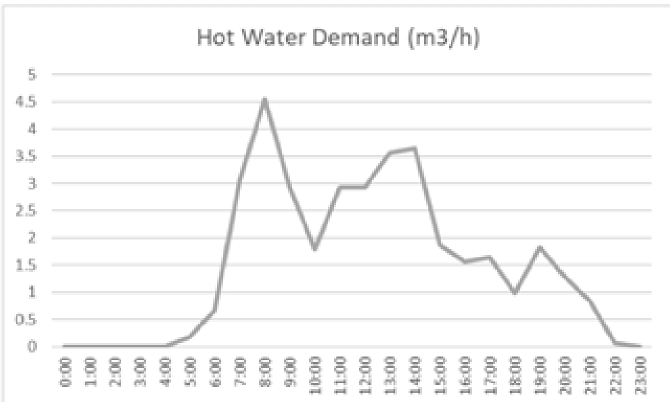

Figure 3 – hot water demand (sanitary use)

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2. Trigeneration scheme

The trigeneration scheme simulated at this study is revealed at figure 4.

Engine jacket energy is recovered by the hot water primary circuit (PC). Water leaves the engine [flow 2] and passes in an exhaust gas heat exchanger (EGHE) where it is warmed [flow 3] prior to enter the hot water single effect absorption chiller. After leaving the absorption chiller [flow 4] PC flow passes through HE1 warming the sanitary use hot water that passed at HE2 [flow 12-15]. Engine intercooler energy is recovered in the secondary circuit (SC) at HE2. The energy is used to warm sanitary use hot water. HE2 and HE1 are in a series arrangement.

Sanitary use hot water demand is revealed at figure 3. Sanitary use hot water is warmed from 22.2ºC to 45ºC recovering energy from the engine SC (HE2) and from the engine PC (HE1).

The EGHE is designed to provide energy to the PC flow leaving the engine. It is designed to achieve an approach point of 16.6ºC with flow 2.

EGHE approach point = temperature flow 20 – temperature flow 2 = 16.6ºC

The hot water absorption chiller is selected to recover the PC and exhaust gas energy and to produce chilled water at 7.2ºC with cooling water entering the condenser at 29.5ºC. A COP close to 0.8 is defined for the absorption chillers.

Main design parameters:

- Engines data utilized at this study are revealed at table 1.
- Hot water single effect absorption chiller COP is defined as 0.8 - design condition.
- HE2 design data are 22.2ºC to 40ºC.
- HE1 design data are 30ºC to 45ºC.
- HE2 and HE1 are in a series arrangement.
- Lower engine load is set to 50%.
- EGHE approach point is 16.6ºC.
- Engines operates at electrical dispatch.
- Chilled water at 7.2ºC.
- Electrical chillers COP is 3.5.

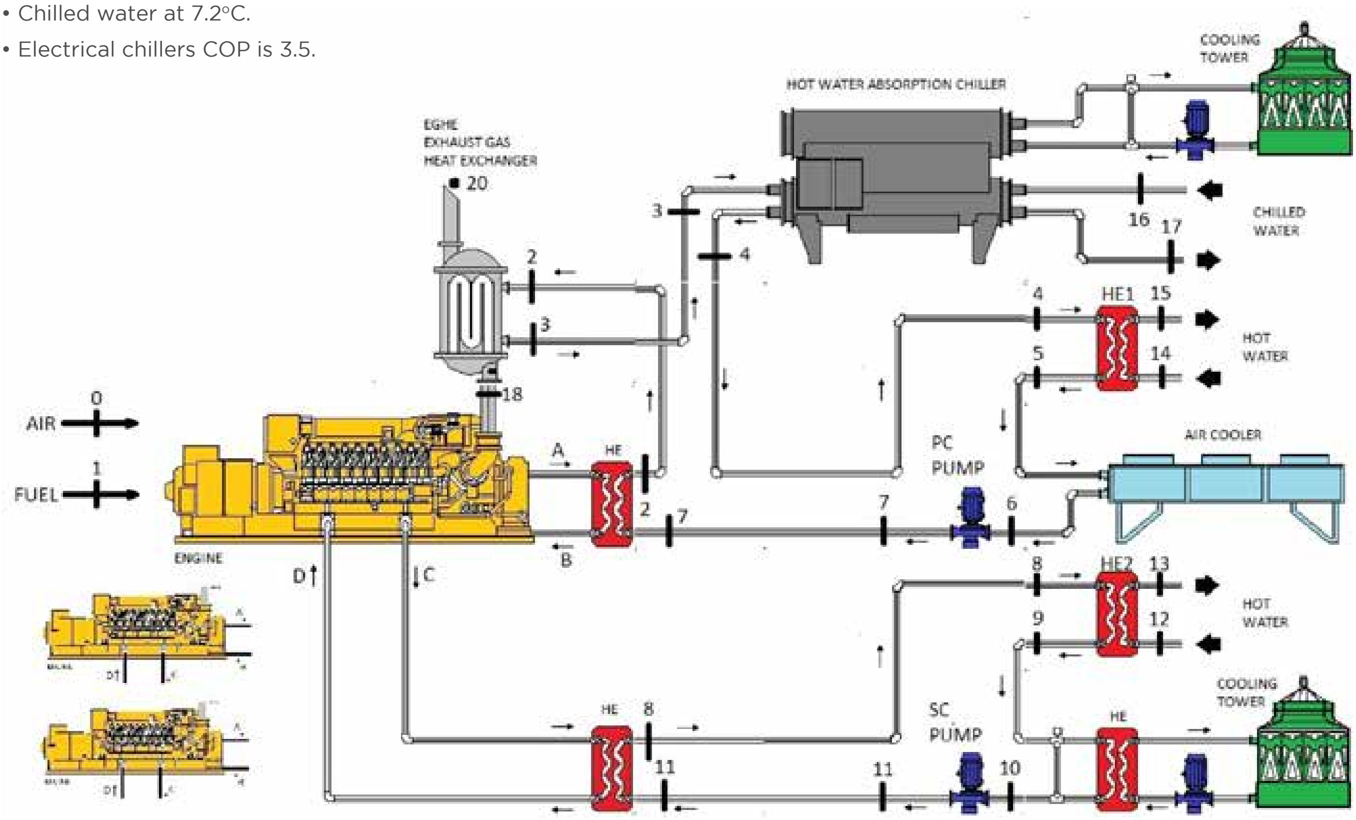

Figure 4 – the trigeneration scheme

The engines performance data utilized in this analysis are shown at table 1. The data were obtained with a Caterpillar dealer. The part load performance curves were built using polynomial regression and are inserted in the software.

Table 1 – engines data

	Engine 1	Engine 2	Engine 3
Model	**CG170-12**	**CG132-12**	**CG132-8**
Engine power (kW)	1200	600	400
Primary circuit energy (kW)	612	297.26	188.17
secondary circuit energy (kW)	116	51.05	27.02
exhaust gas energy (kW)	757	453	317
exhaust gas flow (kg/h)	6531	3349.6	2234.4
exhaust gas temperature (°C)	414	475	493.9
PC water entering/leaving (°C)	80/93	77.8/87.8	83.9/92.2
SC water entering/leaving (°C)	40/43	40/45	40/43.9
electrical efficiency (%)	43.4	41.4	41.4
engine fuel input (kW)	2765	1449.3	966.2

Table 2 – cases 1 to 3 – thermodynamic data

	CASE 1			CASE 2			CASE 3		
flow	pressure (kPa)	temperature (oC)	mass flow (kg/s)	pressure (kPa)	temperature (oC)	mass flow (kg/s)	pressure (kPa)	temperature (oC)	mass flow (kg/s)
0	100	25	1.753	100	25	0.898	100	25	0.599
1	100	25	0.061444	100	25	0.032206	100	25	0.021471
2	462.5	93	11.188	462.5	87.778	7.078	462.5	92.222	5.379
3	375	106.638	11.188	375	101.365	7.078	375	104.64	5.379
4	287.5	81.066	11.188	287.5	80.127	7.078	287.5	84.638	5.379
5	200	80	11.188	200	77.778	7.078	200	83.889	5.379
6	200	80	11.188	200	77.778	7.078	200	83.889	5.379
7	550	80	11.188	550	77.778	7.078	550	83.889	5.379
8	275	43	9.264	275	45	2.428	275	43.889	1.665
9	150	40	9.264	150	40	2.428	150	40	1.665
10	150	40	9.264	150	40	2.428	150	40	1.665
11	400	40	9.264	400	40	2.428	400	40	1.665
12	300	22.222	1.746	300	22.222	1.266	300	22.222	0.462
13	250	38.143	1.746	250	31.814	1.266	250	36.237	0.462
14	250	38.143	1.746	250	31.814	1.266	250	36.237	0.462
15	200	45	1.746	200	45	1.266	200	45	0.462
16	400	13.333	37.572	400	13.333	19.675	400	13.333	14.217
17	300	7.222	37.572	300	7.222	19.675	300	7.222	14.217
18	102	414	1.814	102	475	0.931	102	494	0.621
19	102	414	1.814	102	475	0.931	102	494	0.621
20	100	109.667	1.814	100	104.444	0.931	100	108.889	0.621

- Case 1 is formed by one CG170-12 engine (engine 1).
- Case 2 is formed by two CG132-12 engine (engine 2).
- Case 3 is formed by three CG132-8 engine (engine 3).

Table 2 reveals some thermodynamic data of cases 1 to 3 at design condition.

At the COGMCI software, two and three engines systems are simulated as individual trigeneration systems accordingly with figure 4. It means that in a two engines system there are two independent cog/trig system that can be on or off accordingly with the chosen operational mode and engine load.

HE1 and HE2 are simulated as individual heat exchangers with the engine side (primary and secondary circuits) flow being joined prior to entering HE1/HE2 and divided at the exit, as revealed at figure 5.

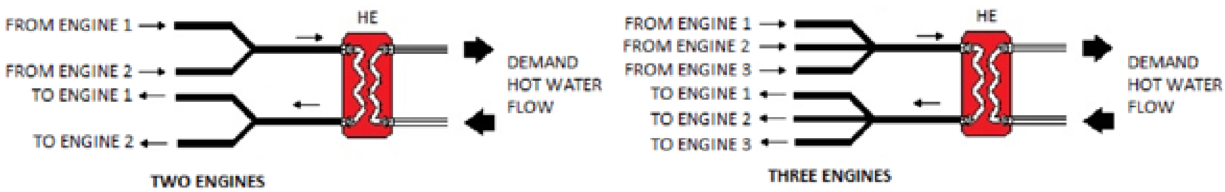

Figure 5 – heat exchangers design with two and three engines systems

Heat exchangers are designed using the NTU method. The engine side (primary and secondary circuit) flow are the individual engine flow multiplied by the number of engines. When the number of engines in operation are lower than in the design condition, the engine side flow is adjusted to the number of engines in operation. Sanitary use hot water demand flow is as defined in the PROFILE DATA screen (figure 3) – flows HE1 and HE2 (flows 12 to 15).

Table 3 – electricity, chilled water and hot water (each engine)

	CASE 1		CASE 2		CASE 3	
	(kW)	(%)	(kW)	(%)	(kW)	(%)
hot water SC	116.06	4.20	50.68	3.50	27.03	2.80
hot water PC	49.95	1.81	69.69	4.81	16.90	1.75
chilled water	966.05	34.94	505.88	34.91	365.55	37.83
steam	0.00	0.00	0.00	0.00	0.00	0.00
power	1164.00	42.10	582.00	40.16	388.00	40.16
SUM	2296.07	83.04	1208.26	83.37	797.48	82.54

Table 3 reveals the engine energy recovery when operating at full load – design condition energy balance. Line 1 reveals the energy recovered from the engine secondary (SC) circuit. SC circuit energy is used to warm sanitary use hot water at HE2. Line 2 reveals the engine jacket water energy (PC) that is used to warm sanitary use hot water at HE1. Line 3 reveals the absorption chiller capacity. Line 5 reveals the engine net power (parasitic power is assumed as 3%). Line 6 reveals the total engine energy possible to be used and the final EUF.

3. Simulated results

Figure 6 reveals the number of engines in operation for the cases 1 to 3. At case 1 the engine is all the time operating. At case 2 one engine operates at hours 0 to 7 and 21 to 23, at the remaining hours two engines are in operation. At case 3 one engine operates at hours 1 to 4 and 23, two engines operate at hours 5 to 11 and 19 to 22 and three engines operates between hours 12 to 18.

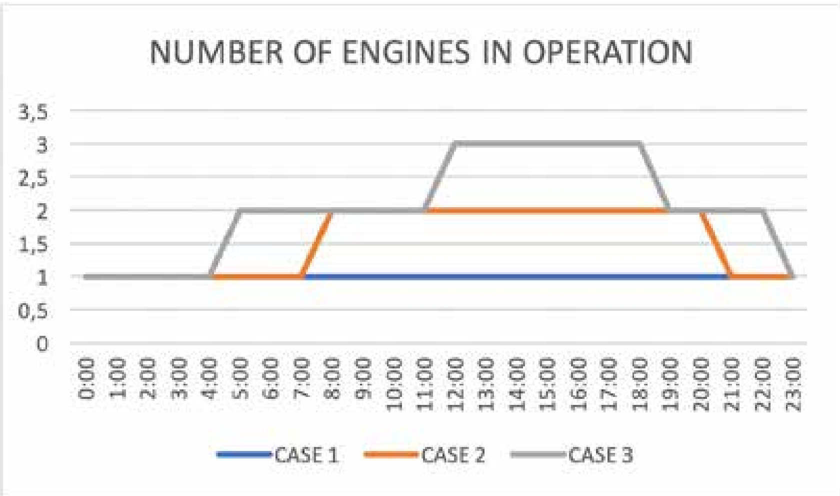

Figure 6 – NEO – number of engines operating

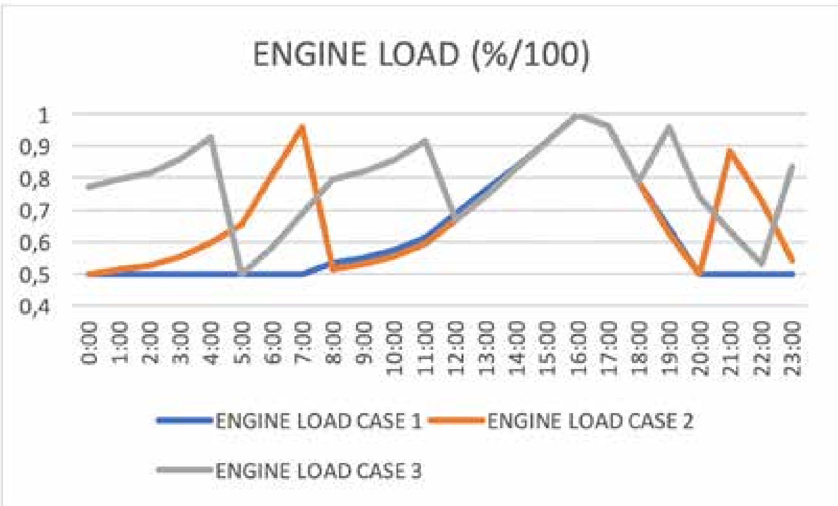

Figure 7 – engine load

Figure 7 reveals the engines load. Case 1 (single engine) operates at 50% load between hours 0 to 7 and 20 to 23. Electricity is exported to the grid since the engine load is limited to 50%. At hours 8 to 19 the engine operates at electrical dispatch following the corrected electricity demand curve (figure 8). The corrected electricity demand curve is the electricity demand profile (figure 1) less the avoided electricity chiller consumption due to the absorption chiller use (electrical chillers COP is 3.5).

At case 2 between hours 0 to 7 and 21 to 23 only one engine is operating and it loads is rising when the electricity demand is rising (hours 0 to 7) and reducing when the electricity demand reduces (hours 21 to 23). Between hour 8 to 20 two engines are working and the electricity demand is being shared. At hour 16 both operates at 100% load.

At case 3 one engine operates until hour 4 with a rising load between 78% (hour 0) and 92% (hour 4). Between hour 5 to 11 two engines shares the electricity demand. At hour 12 two engines are not able to reach the electricity demand and 3 three engines needs to operate. Three engines operate until hour 18. Two engines operate between hours 19 to 22 and one engine at hour 23.

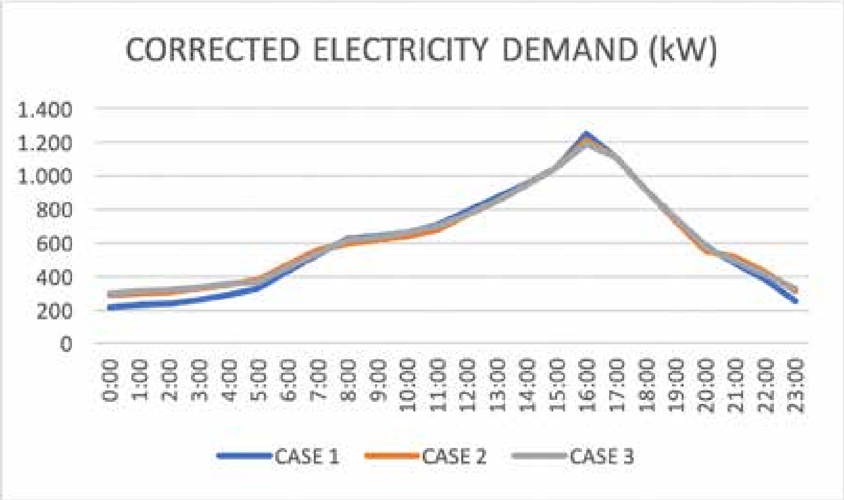

Figure 8 – corrected electricity demand

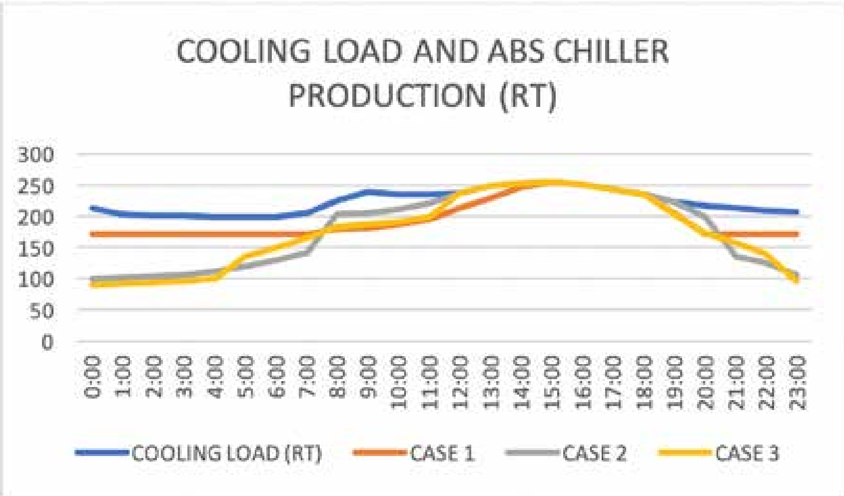

Figure 9 – cooling load and absorption chiller production

Figure 9 reveals the cooling load and the absorption chiller production. Case 1 has the higher absorption chiller production since the engine load is limited to 50%. Cases 2 and 3 have their absorption chiller production as a function of how many engines are operating and how is the engines load. Between hours 15 and 18 the cooling load is met by the absorption chillers at cases 1 to 3 – absorption chiller operates at part load. At the hours the cooling load is not met by the absorption chillers, the electrical chillers should operate to complement the chilled water demand.

Figure 10 reveals the EUF. EUF is the sum of the fuel energy converted to electricity, chilled water (absorption chiller) and hot water. It's a function of the demands (figures 1-3), the engine CHP system design condition (tables 2 and 3), engine load part load performance, etc. All the cases have similar results. Between hours 14 and 18 a fraction of the PC energy is not recovered in the absorption chiller since the cooling load is met and the absorption chiller operates at part load (bypassing PC flow). At these hours the sanitary use hot water demand is being attended – cases 2 and 3 have almost coincident results.

An average engine load of 61.9%, 68.7% and 78.9% was calculated for cases 1, 2 and 3 respectively.

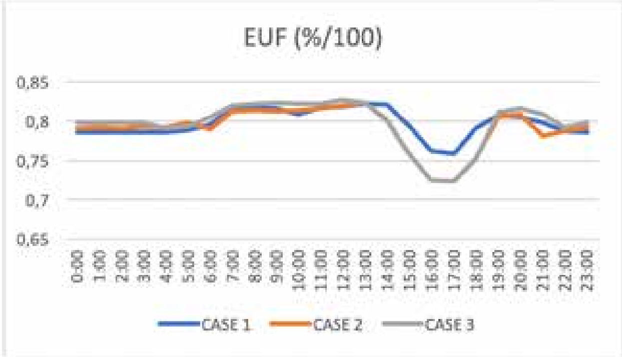

Figure 10 – Energy utilization factor

Table 4 - Results Summary

		CASE 1	CASE 2	CASE 3
1	ELECTRICITY DEMAND (kWh/DAY)	19180.0	19180.0	19180.0
2	CORRECTED ELECT DEMAND (kWh/DAY)	14504.9	14882.1	14945.8
3	NET ELECTRICITY PRODUCTION (kWh/DAY)	17175.0	14841.9	14921.3
4	GRID ELECTRICITY IMPORT (kWh/DAY)	-2670.2	40.2	24.5
5	HOT WATER DEMAND (kWh/DAY)	961.0	961.0	961.0
6	HOT WATER PRODUCTION HE2 (kWh/DAY)	718.8	655.8	610.8
7	HOT WATER PRODUCTION HE1 (kWh/DAY)	16.8	105.3	135.1
8	SURPLUS HOT WATER (kWh/DAY)	225.4	199.8	215.0
9	ENGINE FUEL CONSUMPTION (kWh/DAY)	43129.3	38880.0	38359.7
10	ENGINE AVERAGE EFFICIENCY (%/100)	0.398	0.382	0.389
11	AVERAGE EUF (%/100)	0.798	0.791	0.797

4. Conclusions

The choice between single or multiple engines depends on several factors (I) energy demand curves (ii) engines design performance data, (iii) engine part load data, (iv) electricity exporting and importing rules, (v) engine constraints, (vi) design conditions, (vii) electrical grid reliability, (viii) engine CHP design energy balance, etc.

At this study all solutions produced good results. Table 4 reveals the main simulated results. Line 1 reveals the daily electricity consumption and line 2 the daily corrected electricity consumption (avoided electricity consumption in the electrical chillers due to the absorption chiller is taked into account). Line 3 reveals the engines produced electricity. Since case 1 (engine 1) was limited to operate with a load lower than 50%, the daily analysis revealed that electricity is being exported to the grid (line 4 of table 4). Cases 2 and 3 needs to import a few kWh of electricity.

Hot water demand is not met by any case and additional energy should be used to warm sanitary use hot water to the design condition (lines 5 to 8). Case 2 produced more hot water since it works with higher temperature at the SC and has more energy available at HE1 (flow 4 temperature is close to 2.4°C above flow 7 temperature – table 2).

A more detailed result analysis is not revealed at this study but can be checked in the COGMCI software results.

Despite engine 1 has a higher nominal power and the lower average operational load, the average thermal efficiency is higher than cases 2 and 3 (line 10 – table 4), since engine 1 has a higher thermal efficiency (table 1 – 43.4%). We could expect that multiple engines operating at higher loads would have a higher average thermal efficiency, but the defined study assumptions don't lead to this result.

EUF are very similar in the design mode (table 3) and in the simulated results (figure 4). In the simulated results case 1 revealed a higher EUF mainly due to the higher engine thermal efficiency.

Single engine systems operating at reduced load can have PC temperatures below the required by the absorption chiller. Part load operation needs a detailed analysis.

Single and multiple engines cog/trig systems can operate with high efficiency and met design and strategic goals. Better solution needs a detailed analysis and a compromise between the project goals. Single engine usually has a lower initial investment. Multiple engines can partially attend the energy demands at engines overhauls and failures.

To simplify the analysis developed at this study, one day (24 hours) demand profile curves are utilized, but typical days analysis representing the different annual demands are recommended for practical decisions.