LOOKING FOR THE BEST ENGINE CHP SIZE AND OPERATIONAL MODES FOR TEMPERATE CLIMATE MALLS – 8760 HOURS ANALYSIS

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Introduction

In this Case Study, the COGMCI Software team discusses (i) the best size of an engine CHP system and (ii) what the efficiency indicators tell us about the system performance? What is the best performance indicator?

To start the discussion, COGMCI software is used to simulate and predict the performance of ten different engine CHP case studies for a mall supposed to be located in New York (8760 hours analysis). The building energy demand is predicted using the EnergyPlus software and the results (building energy consumption) are used as COGMCI software input.

Engine CHP is 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) CO2 emissions reduction, or (iv) a combination of them.

The study reveals that engine CHP can save up to 40% primary energy when using the harmonized reference conversion efficiency defined at the EU 2015/2402 directive and a high-efficiency electrical chillers COP.

The shopping mall

The mall is a one-floor building with a total of 61,800 m^2. The building model was constructed in EnergyPlus with five different zones as revealed in figures 1 and 2. The building is located in NYC and the design and simulation conditions used the weather file: USA_NY_New York Central Park.

Building construction was defined as (i) exterior walls: ASHRAE 189.1-2009 ExtWall Mass ClimateZone 5 and (ii) roof: ASHRAE 189.1-2009 ExtRoof IEAD ClimateZone 2-5.

The HVAC system should maintain the mall at 24^{o}C in summer (cooling hours) and at 20^{o}C in winter (heating hours).

The building mall stores are assumed to operate everyday between hours 10 and 22 (zones 1 to 4). Halls, aisles, restaurants, pubs, and food courts are open until midnight (zone 5). HVAC system operates all days between hours 9 to 24, but from November to March the mall heating system (including the air handlers - fan coils) is assumed to operate 24 hours/day.

Lights electric use is assumed to be 10 W/m^2. It is also assumed that 20% of the lights are on between 0 and 9 am, while 100% is on in the remaining hours.

Occupation is assumed as 0.2 person/m^2, resulting in a maximum value of 12.360 persons. No persons are in the mall between hours 0 and 9 (0%), 20% at 10 am, 80% between hours 11 and 14, 60% between hours 15 and 18, 100% between hours 19 and 22 and 40% at hours 23 and 24. Persons are assumed to be in light work with a heat dissipation equal to 130 W/person.

General equipment dissipation is 5 W/m^2 for zone 5 and 1 W/m2 at zones 1 to 4. Equipment dissipation profile is 0% until hour 9, 40% until hour 12, 60% until hour 17, 80% until hour 19, 100% until hour 22 and 40% until hour 24.

Infiltration occurs 100% of the time at a rate of 1 air change per hour. HVAC promotes exterior air to enter the building at a rate of 0.0075 m^3/hour.person (ventilation).

Big malls usually have a high cooling load and high-efficiency equipment is normally used. In this study, a chiller with a COP equal to 6 is assumed (water-cooled centrifugal compressor chiller). Chilled water is produced between 12 and 7ºC and condensed water is between 29 and 35ºC.

Heating is provided by fuelled boilers with 92% efficiency, hot water is delivered to the air handlers heating coils at 90ºC and returns at 60ºC.

Airflow is calculated assuming air leaves the air handler at 14ºC at the design cooling day. Fans are assumed to have a 200 Pa total pressure, 70% efficiency, and an electrical motor with 90% efficiency.

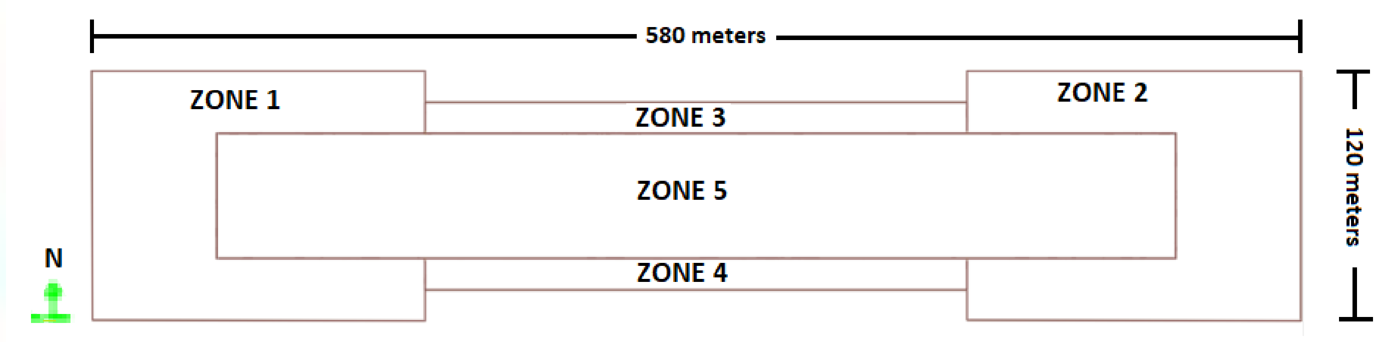

Figure 1 – mall thermal zones

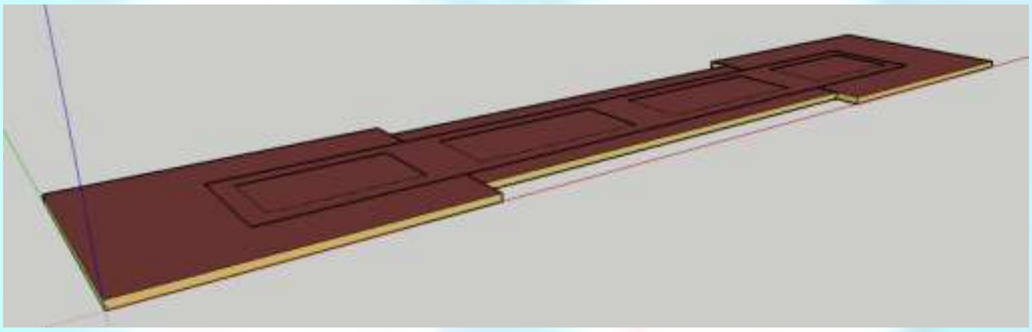

Figure 2 – mall perspective

Figure 1 shows the mall thermal zones and figure 2 reveals the mall perspective view.

Figure 3 shows the annual variation of dry bulb temperature in NYC. Figure 4 reveals the annual relative humidity in NYC. The data was obtained through a TMY EnergyPLus weather file.

Figure 5 reveals the annual building heating and cooling load. Peak heating load was calculated as 11,408.3 kW. Peak cooling load was calculated as 5,372 kW (1526 RT) – which is about 40 m^2/RT.

Figure 6 reveals the facility electricity purchase. In winter days the load profile is pretty similar, since space heating is provided by a gas boiler and equipment dissipation, occupancy, lights use, etc are assumed to be equal at all days. On summer days the electricity purchased is affected by the cooling load. The data reveals that electricity demand is close to 800 kW in winter and has a peak of close to 1800 kW in summer.

Sanitary use hot water consumption occurs only on the mall operating hours. Fuelled boilers are used for sanitary use hot water production. Figure 7 reveals the daily sanitary use hot water energy consumption. Three different curves are used to take into account the water temperature entering the boiler – 20ºC May to august, 15ºC March, April, September, and October, 10ºC November to February. Figure 8 reveals the annual sanitary use hot water energy demand. The mall uses hot water at 50ºC.

Annual building energy consumption totalized 414 kWh/m^2 per year (no energy conversion efficiency).

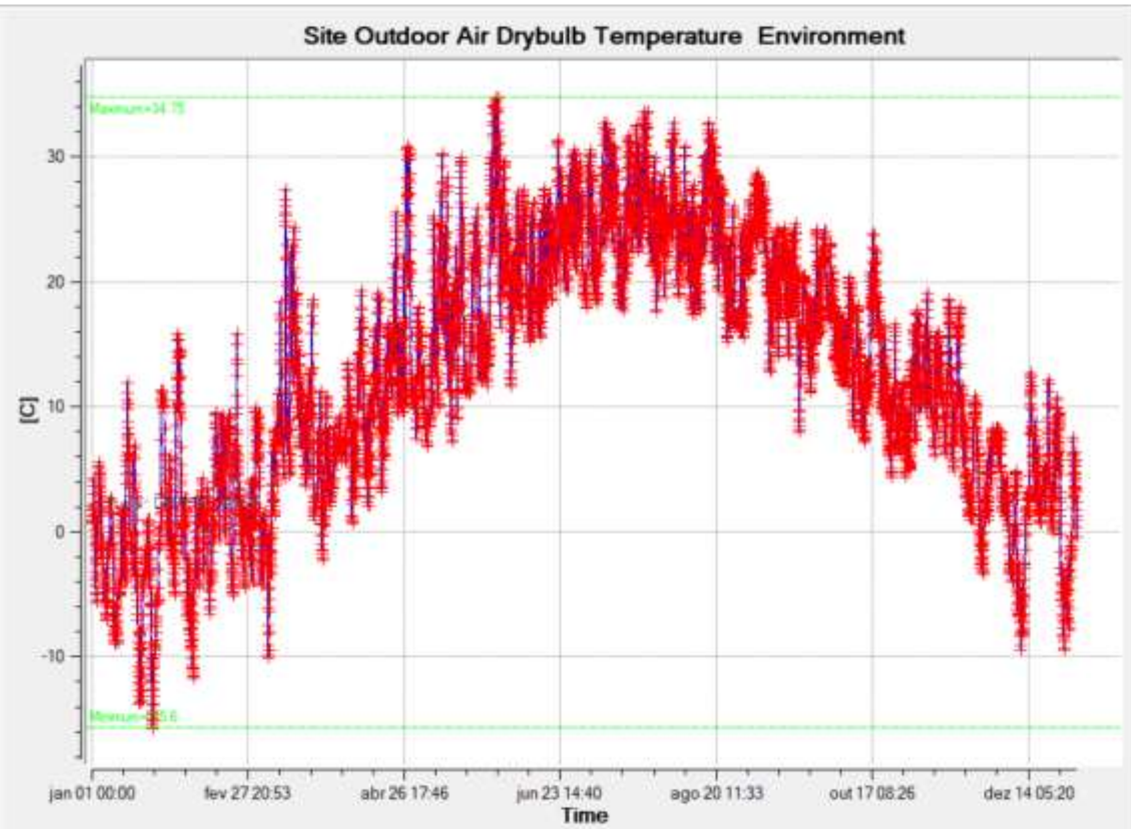

Figure 3 – NYC central park DBT

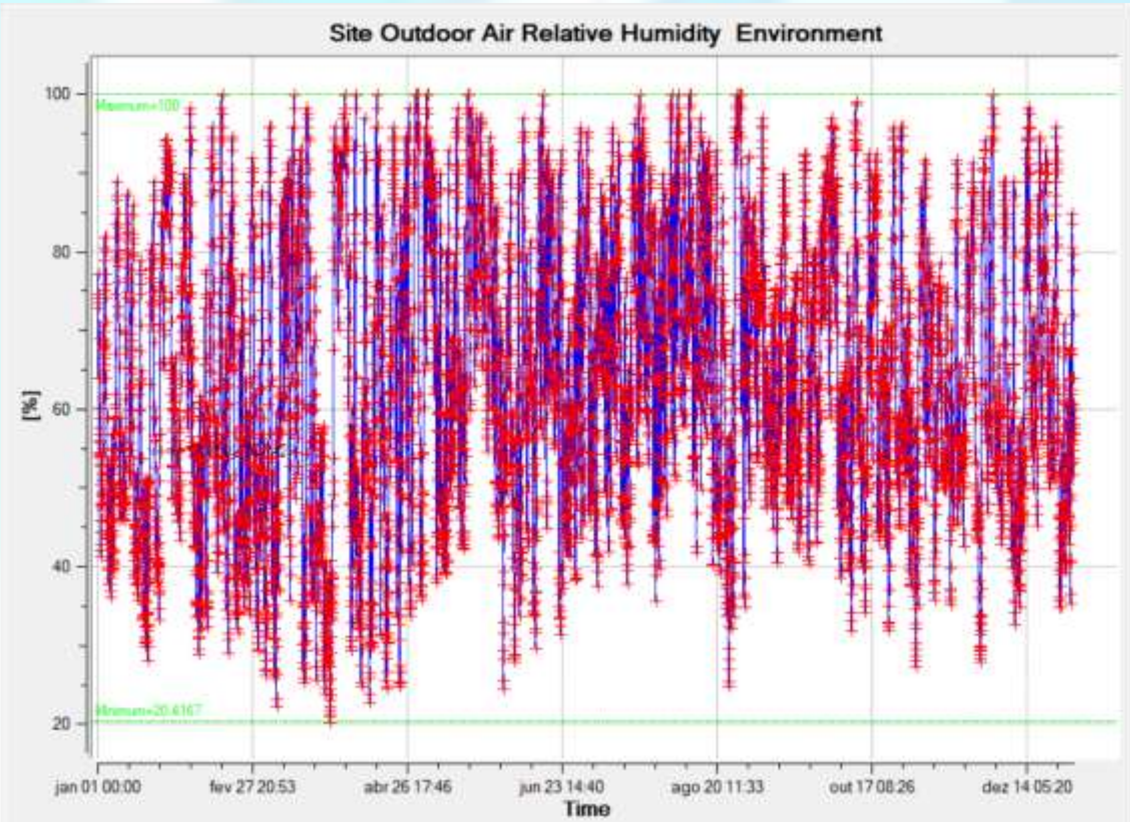

Figure 4 – NYC central park RU

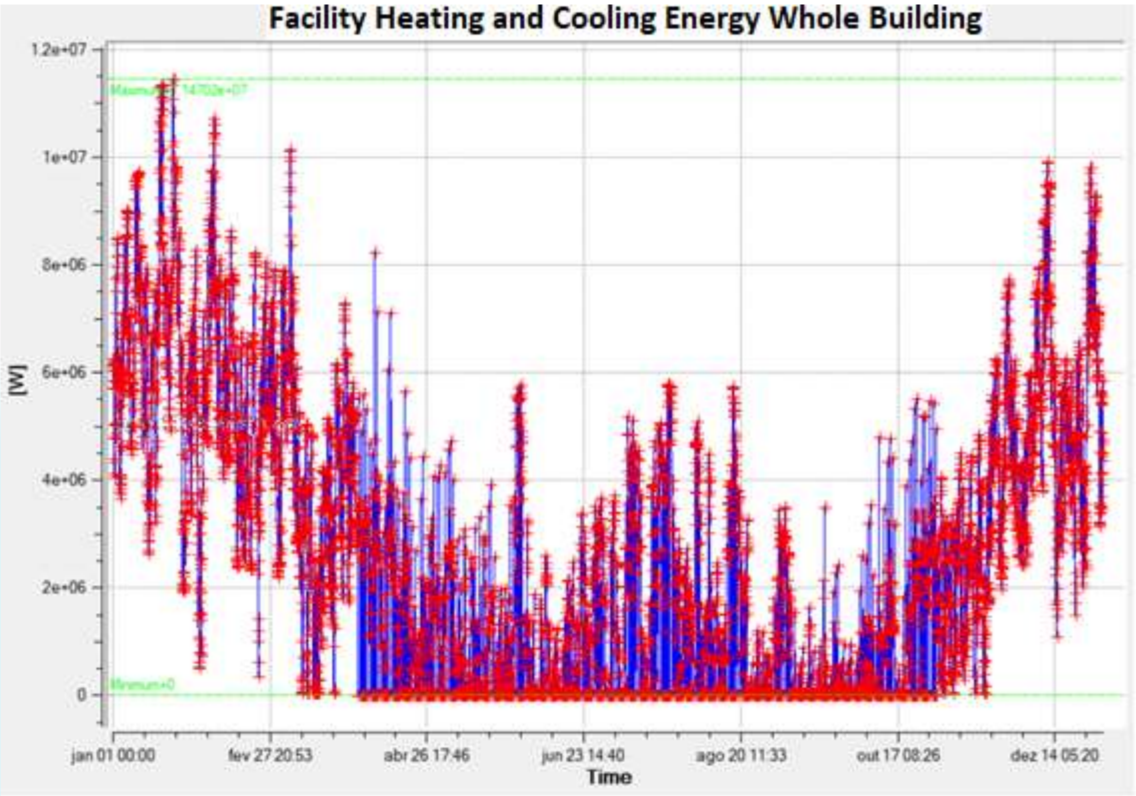

Figure 5 – heating and cooling loads

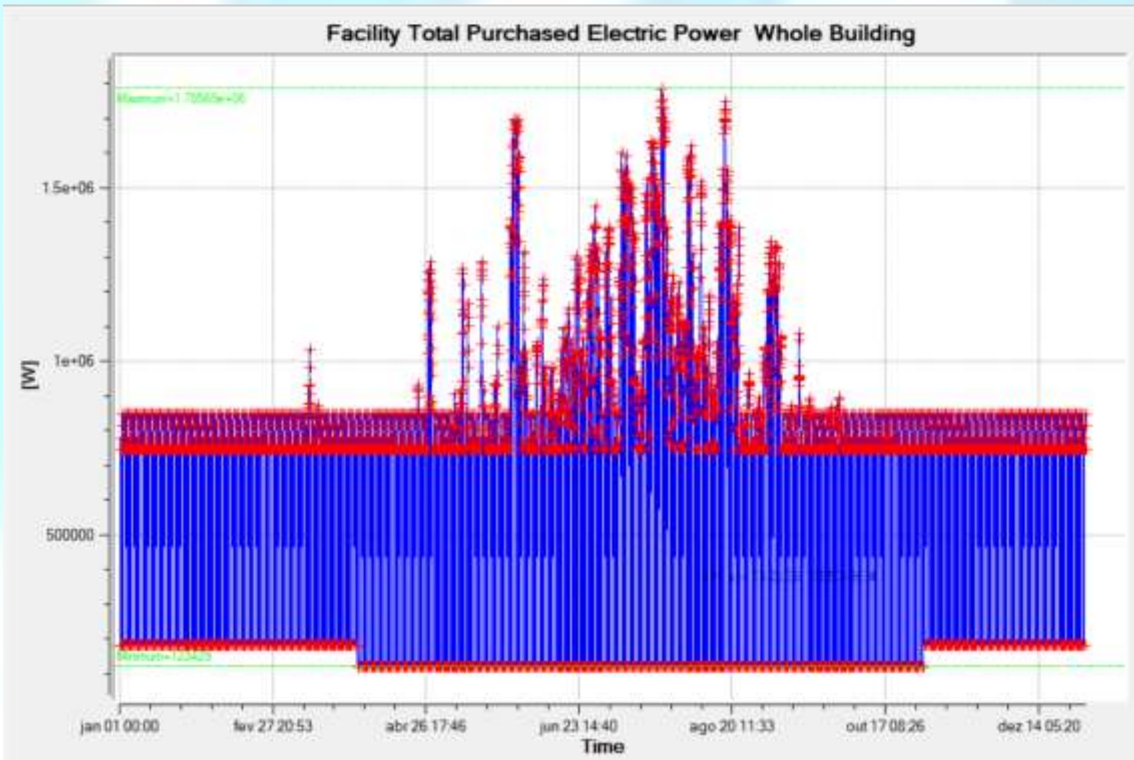

Figure 6 – mall electricity demand

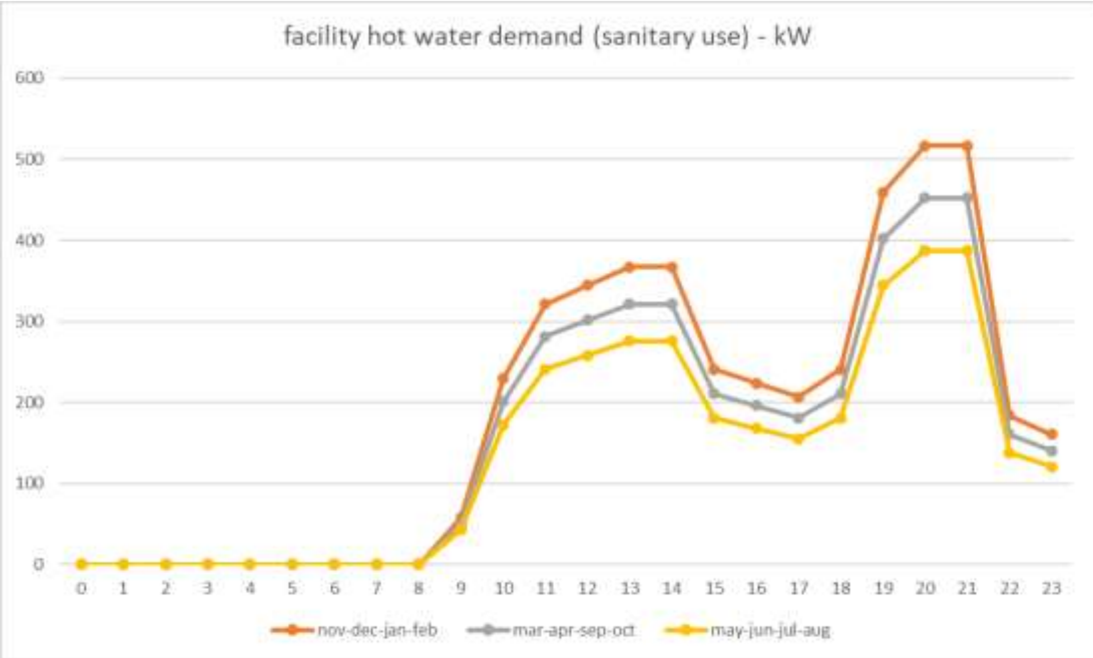

Figure 7 – daily hot water demand (kW)

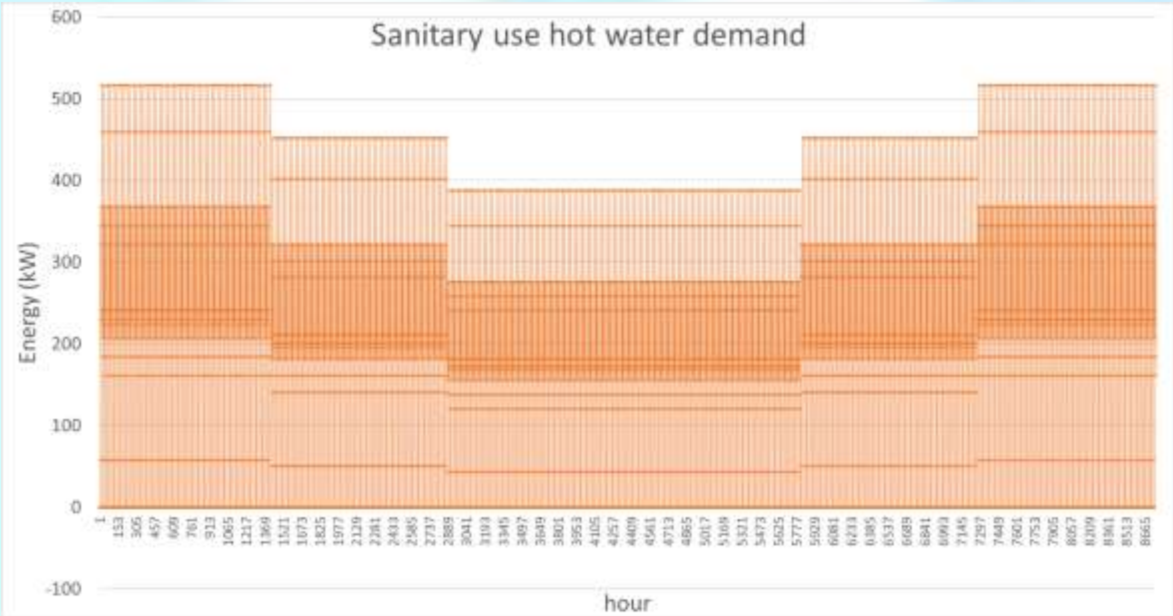

Figure 8 – annual hot water demand profile (kW)

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 single effect hot water absorption chiller, (ii) medium temperature hot water for space heating at HE1 (flows 14 and 15) and (iii) low-temperature hot water at HE2 – sanitary use (flows 12 and 13).

Engine primary circuit (PC) recovers energy from the engine jacket (flow 2) and the engine exhaust gases (EGHE – exhaust gases heat exchanger) – flow 3. The single effect hot water absorption chiller recovers energy from flow 3 to 4. Medium temperature hot water (space heating) recovers energy at HE1 from flow 4 to 5. PC unused energy is rejected on the PC air cooler (flows 5 to 6). PC water at the design condition returns to the engine as flow 7. Secondary circuit (SC) energy is recovered at HE2 – flow 8 to 9. SC unused energy is rejected on SC air cooler.

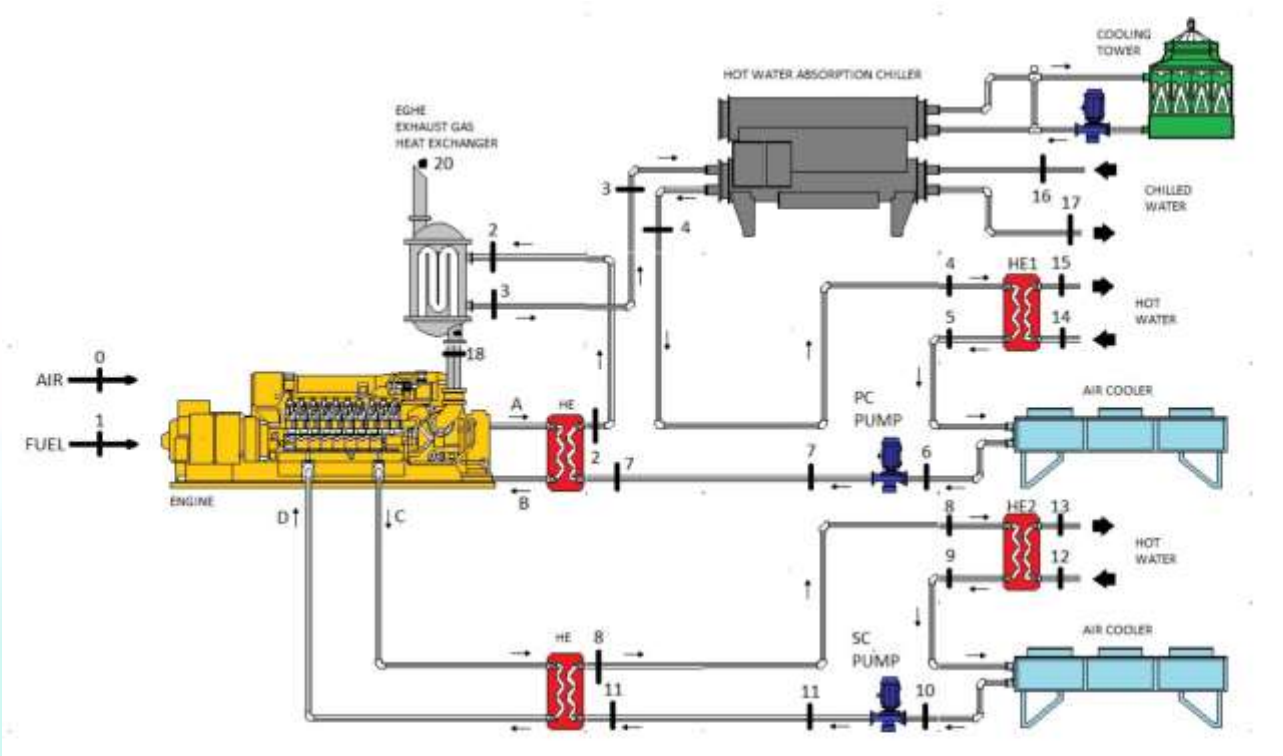

Figure 9 – engine CHP scheme

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	102.47	11.439	429.65	350	105.51	11.188	442.52	350	105.80	14.680	443.73
4	275	86.08	11.439	360.62	275	80.59	11.188	337.57	275	81.04	14.680	339.46
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	22.22	0.606	93.44	300	22.22	1.405	93.44	300	22.22	1.671	93.44
13	250	45.00	0.606	188.57	250	42.00	1.405	176.03	250	43.00	1.671	180.21
14	250	60.00	0.794	251.29	250	60.00	0.220	251.29	250	60.00	0.509	251.29
15	200	85.08	0.794	356.36	200	79.59	0.220	333.31	200	80.04	0.509	335.20
16	400	13.33	25.031	56.35	400	13.33	36.910	56.35	400	13.33	48.163	56.35
17	300	7.22	25.031	30.64	300	7.22	36.910	30.64	300	7.22	48.163	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	102	488.00	1.232	812.81	102	414.00	1.814	728.83	102	420.00	2.386	735.58
20	100	112.00	1.232	400.39	100	113.00	1.814	401.45	100	113.00	2.386	401.45

Table 1 reveals the engine CHP design condition energy products. Three engines are being evaluated at 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) – the detailed data for the summer mode is revealed in table 1. For winter mode the energy between flows 3 and 7 can be used for hot water production on HE1.

EGHE is designed to achieve a 20°C approach point (flow 20 temperature – flow 2 temperature).

Absorption chiller is selected to operate with the same conditions of the existing centrifugal chillers (i) chilled water between 7 and 12°C and (ii) cooling tower water between 35 and 29°C. The absorption chiller COP is 0.8 at the design condition.

Heat exchanges HE1 and HE2 are designed and simulated using the NTU method. HE1 design flow is defined for the maximum energy recovery (flow 3 to 5) for each case, warming water from 60°C to 90°C. This is the same condition of the mall space heating water system design. HE2 design flow is defined for the maximum energy recovery (flow 8 to 9) for each case, warming water from 10°C to 50°C. This is the same condition of the mall sanitary use hot water system design.

Table 2 reveals the three different engine energy balance operating using the PC energy in the absorption chiller (chilled water production) – summer mode. Table 3 reveals the three different engine energy balance operating using the PC at HE1 (hot water production) – winter mode.

Table 2 – engine CHP energy balance – summer mode

	800 kW ENERGY		1200 kW ENERGY		1560 kW ENERGY	
	(kW)	(%)	(kW)	(%)	(kW)	(%)
hot water SC	57.65	3.00	116.04	4.20	144.99	4.00
hot water PC	83.42	4.34	18.05	0.65	42.71	1.18
chilled water	643.60	33.47	949.03	34.32	1238.37	34.13
electricity	784.00	40.77	1176.00	42.53	1528.80	42.14
SUM	1568.67	81.57	2259.12	81.70	2954.87	81.45

Table 3 – engine CHP energy balance – winter mode

	800 kW ENERGY		1200 kW ENERGY		1560 kW ENERGY	
	(kW)	(%)	(kW)	(%)	(kW)	(%)
hot water SC	57.65	3.00	116.04	4.20	144.99	4.00
hot water PC	889.10	46.23	1201.48	43.45	1594.10	43.94
chilled water	0.00	0.00	0.00	0.00	0.00	0.00
electricity	784.00	40.77	1176.00	42.53	1528.80	42.14
SUM	1730.75	90.00	2493.52	90.18	3267.89	90.08

The 800 kW engine CHP system produces 784 kW (40.77% electrical efficiency) of net electricity (2% is parasitic power – fans and pumps). In the summer mode it can produce 643.6 kW of chilled water at the absorption chiller (33.47%) and 83.42 kW of hot water at HE1 (4.34%) – table 2. In the winter mode it can produce 889.1 kW of hot water for space heating (46.23%) – table 3. At both modes, 57.65 kW (3%) can be used for low-temperature hot water production. A EUF equal to 81.57% in summer mode and 90% on winter mode can be reached.

The 1200 kW engine CHP system produces 1176 kW (42.53% electrical efficiency) of net electricity (2% is parasitic power). In the summer mode it can produce 949.03 kW of chilled water at the absorption chiller (34.32%) and 18.05 kW of hot water at HE1 (0.65%) – table 2. In the winter mode it can produce 1201.48 kW of hot water for space heating (43.45%) – table 3. At both modes, 116.04 kW (4.2%) can be used for low-temperature hot water production. A EUF equal to 81.7% in summer mode and 90.18% on winter mode can be reached.

The 1560 kW engine CHP system produces 1528.8 kW (42.14% electrical efficiency) of net electricity. In the summer mode, it can produce 1238.37 kW of chilled water at the absorption chiller (34. 13%) and 42.71 kW of hot water at HE1 (1.18%) – table 2. In the winter mode it can produce 1594.1 kW of hot water for space heating (43.94%) – table 3. At both modes, 144.99 kW (4%) can be used for low-temperature hot water production. A EUF equal to 81.45% in summer mode and 90.08% on winter mode can be reached.

The lower engine load is limited to 50% (default value).

10 different solutions are evaluated:

- Case 1: one 800 kW engine operating at full load.
- Case 2: one 800 kW engine operating at thermal dispatch with 70% minimum EUF.
- Case 3: one 1200 kW engine operating at electrical dispatch.
- Case 4: one 1200 kW engine operating at thermal dispatch with 70% minimum EUF.
- Case 5: one 1560 kW engine operating at electrical dispatch.
- Case 6: one 1560 kW engine operating at thermal dispatch with 70% minimum EUF.
- Case 7: two 1200 kW engines CHP systems operating at thermal dispatch with 70% minimum EUF.
- Case 8: three 1200 kW engines CHP systems operating at thermal dispatch with 70% minimum EUF.
- Case 9: two 1560 kW engines CHP systems operating at thermal dispatch with 70% minimum EUF.
- Case 10: three 1560 kW engines CHP systems operating at thermal dispatch with 70% minimum EUF.

Table 4 – engine CHP cases main results

		CASE 1	CASE 2	CASE 3	CASE 4	CASE 5	CASE 6	CASE 7	CASE 8	CASE 9	CASE 10
		800FL	800TD70	1200ED	1200TD70	1560ED	1560TD70	1200TD70x2	1200TD70x3	1560TD70x2	1560TD70x3
	ELECTRICITY										
1	electricity consumption (kWh/year) =	5,232,839	5,232,839	5,232,839	5,232,839	5,232,839	5,232,839	5,232,839	5,232,839	5,232,839	5,232,839
2	electricity production (kWh/year) =	5,456,995	4,918,480	5,428,928	7,319,146	5,749,501	9,408,538	13,243,085	18,414,827	16,635,508	22,462,686
3	electricity production - net (kWh/year) =	5,347,855	4,820,110	5,320,350	7,172,763	5,634,511	9,220,367	12,978,223	18,046,530	16,302,798	22,013,432
4	avoided electricity abs chiller (KWh/year) =	128,020	128,020	166,001	179,526	183,037	223,863	306,643	391,614	362,778	440,738
5	aditional electricity (kWh/year) =	-243,036	284,709	-253,512	-2,119,450	-584,708	-4,211,391	-8,052,027	-13,205,305	-11,432,737	-17,221,331
6	engine fuel consumption (kWh/year) =	13,111,507	11,962,710	13,124,332	17,030,257	14,407,877	22,156,101	30,727,064	42,766,930	39,077,153	52,880,826
	HOT WATER										
7	Hot water consumption PC (kWh/year) =	18,957,600	18,957,600	18,957,600	18,957,600	18,957,600	18,957,600	18,957,600	18,957,600	18,957,600	18,957,600
8	Hot water consumption SC (kWh/year) =	1,415,237	1,415,237	1,415,237	1,415,237	1,415,237	1,415,237	1,415,237	1,415,237	1,415,237	1,415,237
9	Hot water production PC (kWh/year) =	3,866,308	3,866,308	3,641,941	5,134,901	4,203,078	6,676,469	9,586,806	13,100,810	12,009,169	15,675,923
10	Hot water production SC (kWh/year) =	312,098	263,509	384,395	507,486	364,250	612,442	756,454	837,607	838,496	883,064
11	aditonal hot water PC (kWh/year)=	15,091,292	15,091,292	15,315,658	13,822,699	14,754,522	12,281,131	9,370,793	5,856,790	6,948,430	3,281,677
12	aditional hot water SC (kWh/year)	1,103,140	1,151,728	1,030,842	907,751	1,050,988	802,795	658,783	577,630	576,741	532,174
13	aditional hot water SC+PC (kWh/year) =	16,194,431	16,243,020	16,346,500	14,730,450	15,805,510	13,083,926	10,029,577	6,434,420	7,525,172	3,813,851
	CHILLED WATER										
14	Chilled water demand (RT/year) =	837,448	837,448	837,448	837,448	837,448	837,448	837,448	837,448	837,448	837,448
15	chilled water production (RT/year) =	218,400	218,400	283,197	306,270	312,259	381,908	523,130	668,089	618,895	751,894
	EUF, LOAD AND PAYBACK										
16	AVERAGE EUF (%)	78.51	81.24	78.81	81.57	78.43	80.58	81.89	80.28	80.17	77.94
17	AVERAGE ENGINE LOAD (%)	100.00	90.15	66.38	89.43	54.08	88.43	92.19	91.55	90.73	88.78
18	PAYBACK (YEARS)	1.65	1.78	2.49	1.86	3.05	1.90	2.08	2.27	2.17	2.44
	COMPLETE PES										
19	PEC without cog/trig (kWh/year) =	33,772,919	33,772,919	33,772,919	33,772,919	33,772,919	33,772,919	33,772,919	33,772,919	33,772,919	33,772,919
20	PEC with cog/trig (kWh/year) =	30,197,052	30,250,853	30,352,880	28,532,147	30,343,718	27,417,352	24,496,805	21,664,471	22,931,716	20,385,187
21	PES =	10.59	10.43	10.13	15.52	10.15	18.82	27.47	35.85	32.10	39.64
	EUROPEAN UNION DIRECTIVE - PES										
22	PES =	15.23%	17.04%	15.32%	18.27%	14.19%	17.27%	18.56%	17.37%	17.02%	15.27%
23	PES <0.45KV =	23.87%	25.29%	23.91%	26.03%	22.59%	24.77%	25.58%	24.33%	24.04%	22.37%
24	PES <12KV=	21.46%	22.98%	21.51%	23.87%	20.25%	22.68%	23.64%	22.41%	22.09%	20.41%
	ETE - EQUIVALENT THERMAL EFFICIENCY										
25	ETE (no grid loss) =	63.90%	66.21%	62.72%	67.47%	61.60%	66.35%	68.18%	66.77%	66.36%	64.37%
26	ETE (10% grid loss) =	71.00%	73.56%	69.68%	74.97%	68.45%	73.73%	75.76%	74.18%	73.74%	71.52%
27	ETE (20% grid loss) =	79.87%	82.76%	78.40%	84.34%	77.01%	82.94%	85.23%	83.46%	82.96%	80.46%

Results Discussion

Table 4 reveals the engine CHP cases main results.

Line 1 reveals the mall annual electricity consumption (kWh/year), calculated using figure 6 data (EnergyPlus results).

Line 2 reveals the CHP annual power production (kWh/year). Cases 1, 2, 3 and 5 produces close to the mall consumption (less than 11% is imported/exported), while cases 4 and 6 to 10 exports close to 40% (case 4), 80% (case 6), 153% (case 7), 252% (case 8), 218% (case 9) and 329% (case 10) of the mall electricity consumption.

Line 3 reveals the CHP net electricity production (kWh/year) assuming a 2% parasitic load. Line 4 reveals the avoided annual electricity (kWh/year) due to the absorption chiller use. Line 15 reveals the annual absorption production (RT/year – Refrigeration Tons). Line 4 results are equal line 15 results multiplied by the existing centrifugal chillers efficiency (0.587 kW/RT ~ COP=6).

Line 5 reveals the electricity import/export in kWh/year (negative values means electricity is being exported).

Line 6 reveals the engine fuel consumption (kWh/year).

Line 7 reveals the mall medium temperature hot water (space heating) energy consumption (kWh/year) – heating load on figure 5 (EnergyPLus results). Line 8 reveals the mall low-temperature hot water (bathrooms and kitchens use) energy consumption (kWh/year) – figure 8.

Line 9 reveals the engine CHP cases medium temperature annual hot water production (kWh/year) and line 10 reveals the engine CHP low temperature annual hot water production (kWh/year). Low temperature (sanitary use) demand temperature (50ºC) is not reached by the engine CHP cases, since the engine SC water temperature leaving the engine (flow 8) is lower than the demand design condition (50ºC) for all engines.

Lines 11, 12, and 13 reveal the surplus annual energy necessary to meet the hot water consumption (kWh/year).

Line 14 reveals the annual cooling load (RT/year) – figure 5 cooling load converted to RT (EnergyPLus results). Line 15 reveals the engine CHP cases annual chilled water production (RT/year).

Line 16 reveals the average annual EUF (Energy Utilization Factor). Case 2, 4, and 7 revealed the higher values, 81.24%, 81.57%, and 81.89% respectively. Cases 1, 3, 5, and 10 are all close to 78% EUF. Case 6, 8, and 9 revealed a EUF close to 80%. Comparing the single-engine cases it can be noted that the thermal dispatch operational mode always produces a better result due to a better match between the engine residual energy use and the site energy demands. At COGMCI software when operating multiple engine systems at thermal dispatch, some engines can be shut down when the minimum defined EUF is not reached.

Line 17 reveals the engine CHP cases average engine load. Higher engine loads occurred in electrical base load systems (cases 1 and 2). Electrical dispatch mode also revealed high engine load (cases 4 and 6 to 10), but with multiple engines, the engine load is only referenced to the engine that is operating.

Line 18 reveals the payback scenario. The economic scenario assumes an installed cost of U$ 1500/kW and that electricity is exported to the grid by the same price it is bought from the grid. Cases 3 and 5 (electrical dispatch mode) exports a few electricity (lower engine load) and revealed the worst results. Higher engine loads trends to reduce the payback period.

Line 19 reveals the Mall PEC assuming hot water is produced by fueled boilers with 92% efficiency and electricity is produced in centralized thermal plants with an average 45% efficiency (using equation 3 – annex I). It is the same for all cases.

Line 20 reveals the PEC of the engine CHP cases calculated using equation 10. Surplus hot water is produced by fueled boilers with 92% efficiency. Electricity is imported from the grid assuming an average thermal efficiency of 45% and is exported to the grid assuming an avoided electrical production with 47% thermal efficiency. Lower PEC occurs for systems exporting electricity to the grid, since in equation 10 exporting electricity is computed as a negative value. Despite a higher fuel consumption (line 6) due to electricity export, a higher fraction of the site thermal demands are met. Line 21 reveals the PES between 10.13% and 39.64% - equation 16. Better cases are the ones that export more electricity to the grid while matching most of the thermal loads – case 10 revealed the higher PES.

Line 22 reveals the PES calculated accordingly with the EU directive. EU directive uses CHP electrical efficiency and thermal efficiency. Cases with high EUF trends to have better results, but thermal and electrical efficiency have different participation – equation 17 annex II. Reference boiler efficiency is defined as 92% and reference centralized thermal plant efficiency is 53%. PES between 14.2% (case 5) and 18.56% (case 3) was calculated.

Using the EU directive reviewing the harmonized reference efficiency values (avoided grid loss factors) the PES is recalculated in line 23 (connection with the grid at a voltage lower than 450V) and line 24 (connection with the grid at a voltage higher equal than 450V and lower than 12000 V). The results follow the line 22 trend, but a higher PES is calculated. Grid loss factors depend on the imported/exported electricity and also on the connection voltage. The reference thermal efficiency (53%) was adjusted to between 45-46.5% at lower than 450V connection and 47.2-48.3% at lower than 12000V.

ETE (equivalent thermal efficiency) is revealed in lines 25 to 27. At line 25 no grid loss is assumed (equation 14). Equation 15 is used to compute grid loss. A grid loss factor of (i) 0.9 means a 10% grid loss (line 26) and (ii) 0.8 means a 20% grid loss. ETE reveals that all the proposed solutions have higher efficiency that the better available technology of centralized thermal plants (high efficiency combined cycles). ETE between 61.76% (case 5 no grid loss) and 85.23% (case 7 with 20% grid loss) were calculated.

A detailed look on case 10

At thermal dispatch mode, the COGMCI software looks for a higher number of engines operating at higher loads. As the defined EUF is not reached with three engines, one engine is turned off. If it is not reached with two engines another engine is turned off. Figure 10 reveals the number of engines operating (NEO) in case 10. The NEO values are represented by the brown lines. The engine CHP case 10 system doesn't operate for 1926 hours/year (night period of April 1 to October 30). For 1888 hours only one engine operates, for 468 hours two engines operate and at 4478 hours three engines are in operation. The blue lines represent the EUF (divided by 100). It can be seen that lower heating and cooling loads (figure 5) trends to reduce the NEO value, allowing the case to operate with high efficiency in most of the operation hours. At some hours no or small heating and/or cooling occurs and the CHP system operates with one engine at a low EUF.

This same analysis was revealed by COGMCI software for cases 7 to 9 (figures not shown).

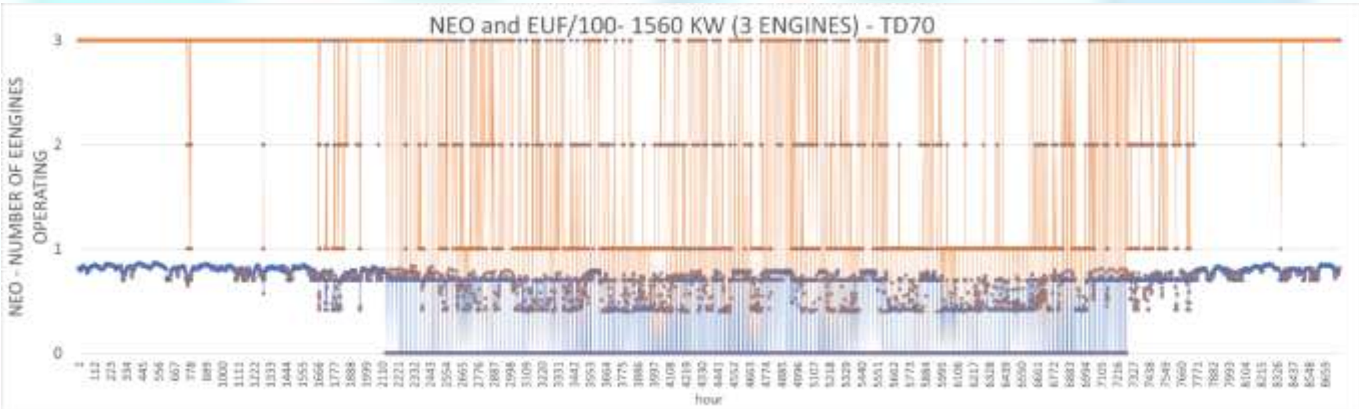

Figure 10 – case 10 - number of engines operating and EUF/100

Conclusions

The EnergyPLus software was used to predict the electrical, heating and cooling loads. When evaluating existing buildings a "refine" can be done adjusting the model to the existing data (gas and electrical bills, existing equipment, measured data, etc). EnergyPlus can build electrical profiles, cooling profiles, and heating profiles on an annual basis. In this case study, the EnergyPlus software results are used to feed the COGMCI software.

Due to high heating loads in winter and high cooling loads in summer a solution with two and three engines revealed a higher PES. Looking to a high EUF at mild climate (some days in autumn and spring) some engine is shut down.

The results are justified due to the engine electrical efficiency and energy balance, including PC and SC water temperatures and exhaust gases flow and temperature at part and full load and also due to heating, cooling, and electrical demands. A detailed discussion of the results requires a detailed results analysis.

A high-efficiency scenario was selected for cooling production (chiller with a COP=6), heating production (boiler efficiency equal to 92%), and electricity production (average thermal efficiency equal to 45% assuming grid losses).

The system's performance were measured through four different indicators: (i) EUF energy utilization factor, (ii) PES primary energy savings using the EU directive, (iii) PES comparing PEC (primary energy consumption) without and with a CHP system and (iv) ETE equivalent thermal efficiency.

EUF is the CHP most used performance indicator. It reveals how much energy is being converted and recovered. It is an important indicator revealing the system performance.

EU Directive formulation (equation 17) uses the system electrical and thermal efficiency (separated EUF) compared to harmonized reference values for separate production of heating and electricity. It evaluates the CHP performance without taking into account the primary energy consumption of the unmet energy demands - energy demands that are not attended by the engine CHP system. A small CHP system (case 1) trends to have similar primary energy savings (in percentage) than a bigger system (case 10). The EU directive calculating the power plants thermal efficiency assuming grid losses is very elucidative as it corrects for grid loss and allows an electricity import/export scenario to be evaluated at different grid voltage connections.

PES using the formulation presented in annex I (equations 3, 10, and 16) also involves the energy demands that are not being supplied by the cog/trigeneration system. That’s why a 10% PES is calculated with small systems and a 40% PES is obtained with a bigger system.

ETE indicates how efficient needs to be the country average thermal efficiency to disregard the benefits of engine CHP systems. ETE results indicates that engine CHP is the best available technology for some applications.

Thermal dispatch operation rises site PES possibilities and can be planned at different approaches: (i) following outside air temperature forecast, (ii) real-time EUF calculation, (iii) similar day benchmark, (iv) combination of previous approaches in an algorithm. Knowledge of the engine CHP part load behavior can help define the operational approach to be used.

A given site with coincident thermal and electrical loads have a CHP potential to reduce CO_2 emissions. Basic analysis does not appropriate the site available potential to reduce CO_2 emissions, most of the time a downsized solution is implemented. The best solution depends on the country production electricity scenario. If the country is looking to improve its average thermal efficiency with resilient thermal plants, high-efficiency engine CHP can help achieve this goal.

COGMCI developers suggest customers, policymakers, stakeholders, and the engineering team to 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 main goals with an attractive payback period.

From the environmental point of view, the PES 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 (better technical solution with the lower payback solution).

The results revealed that oversized engine systems can (i) work as a demand response system, (ii) save more primary energy than small systems, and (ii) can export electricity to the grid at low renewables production hours and/or peak load hours with a high-efficiency operation. 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.

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:

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

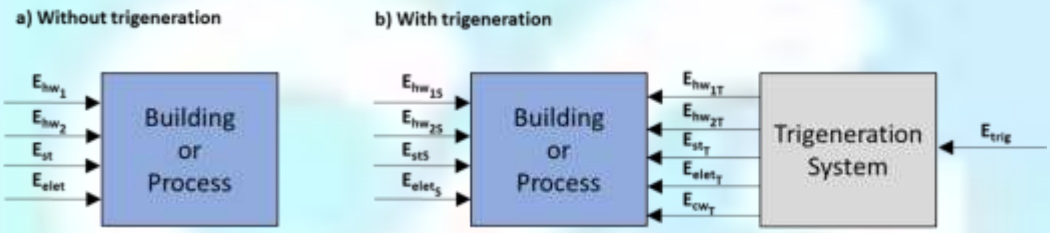

Figure 13 – building/process energy consumption

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

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

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

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

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

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

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

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 harmonised efficiency reference values for separate production of electricity are based on ne calorific value and standard atmospheric ISO conditions (15 °C ambient temperature, 1,013 bar, 60 % relativ humidity)

Category		Type of fuel	Year of construction		
			Before 2012	2012-2015	From 2016
Solids	S1	Hard coal including anthracite, bituminous coal, sub-bituminous coal, coke, semi-coke, pet coke	44,2	44,2	44,2
	S2	Lignite, lignite briquettes, shale oil	41,8	41,8	41,8
	S3	Peat, peat briquettes	39,0	39,0	39,0
	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	33,0	37,0
	S5	Other solid biomass including all wood not included under S4 and black and brown liquor	25,0	25,0	30,0
	S6	Municipal and industrial waste (non-renewable) and renewable/bio-degradable waste	25,0	25,0	25,0
Liquids	L7	Heavy fuel oil, gas/diesel oil, other oil products	44,2	44,2	44,2
	L8	Bio-liquids including bio-methanol, bioethanol, bio-butanol, biodiesel and other bio-liquids	44,2	44,2	44,2
	L9	Waste liquids including biodegradable and non-renewable waste (including tallow, fat and spent grain)	25,0	25,0	29,0
Gaseous	G10	Natural gas, LPG, LNG and biomethane	52,5	52,5	53,0
	G11	Refinery gases hydrogen and synthesis gas	44,2	44,2	44,2
	G12	Biogas produced from anaerobic digestion, landfill, and sewage treatment	42,0	42,0	42,0
	G13	Coke oven gas, blast furnace gas, mining gas, and other recovered gases (excluding refinery gas)	35,0	35,0	35,0
Other	O14	Waste heat (including high temperature process exhaust gases, product from exothermic chemical reactions)			30,0
	O15	Nuclear			33,0
	O16	Solar thermal			30,0
	O17	Geothermal			19,5
	O18	Other fuels not mentioned above			30,0

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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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