ANNUAL PERFORMANCE ANALYSIS OF ENGINE CHP SYSTEMS AT EQUATORIAL CLIMATE MALLS

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Introduction

In this Case Study, the COGMCI Software team discusses (i) the best size of an engine CHP system for an equatorial climate mall and (ii) what the efficiency indicators tell us about the system performance? What performance indicator should be used when looking to reduce the CO2 emission?

To start the discussion, COGMCI software is used to simulate and predict the performance of eight different engine CHP case studies for a mall supposed to be located in Singapore. An 8760 hours analysis is performed. 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) CO_2 emissions reduction, or (iv) a combination of them.

This study reveals that engine CHP can save close to 30% primary energy when using the harmonized reference conversion efficiency defined at the EU 2015/2402 directive and close to 20% 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 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 Singapore and the design and simulation conditions used the weather file: SGP_Singapore.486980_IWEC.epw.

Building construction was defined as (i) exterior walls: double brick walls with 5 cm plaster and a total thickness of 30 cm (U=3.849 W/m^2.K) and (ii) roof: sandwich type roof tile - aluminum plate with 5 cm thermal insulation and aluminum plate (U=0.554 W/m^2.K)).

The HVAC system should maintain the mall at 24^{o}C at all seasons (only cooling hours occurs).

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 every day between hours 9 to 24.

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/m^2 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.

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.

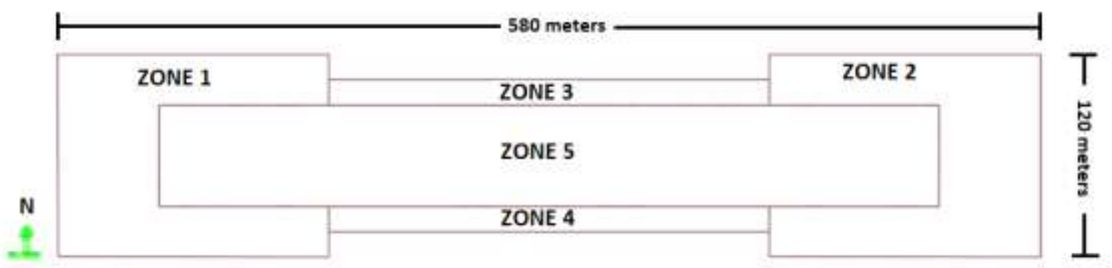

Figure 1 – mall thermal zones

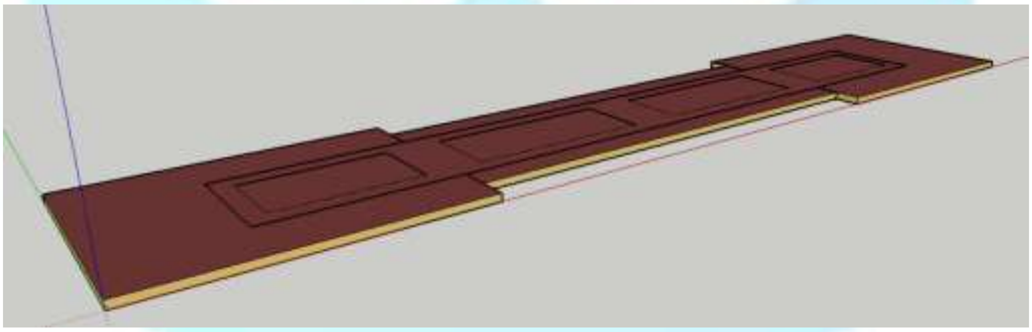

Figure 2 – mall perspective

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

Figure 3 shows the dry bulb temperature annual profile in Singapore. Figure 4 reveals the annual relative humidity profile in Singapore. The data was obtained through an EPW EnergyPLus weather file.

Figure 5 reveals the annual building HVAC electrical power consumption (chiller plus fancoils electrical motors). Fancoil fan power is close to 110 kW. The peak cooling load was calculated as 9,533 kW (2708 RT) – which is about 22.8 m^2/RT.

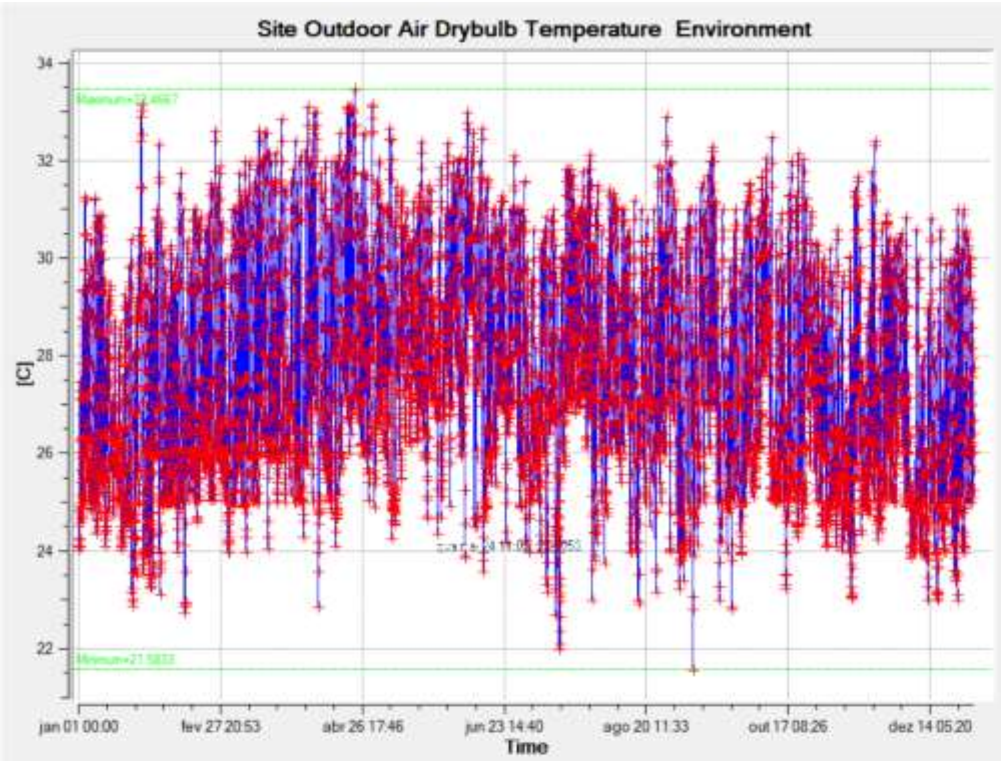

Figure 3 – Singapore annual DBT (°C)

Figure 6 reveals the mall 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 close to 128 kW at night hours (when the mall is closed) and has a peak of close to 2500 kW.

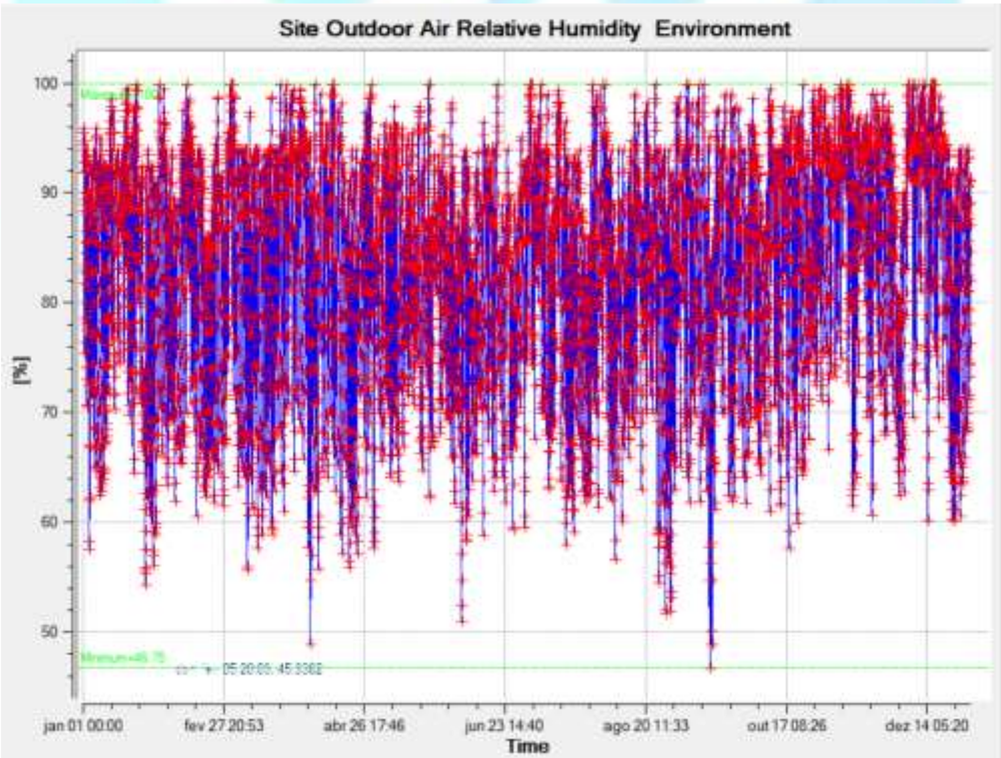

Figure 4 – Singapore annual RH (%)

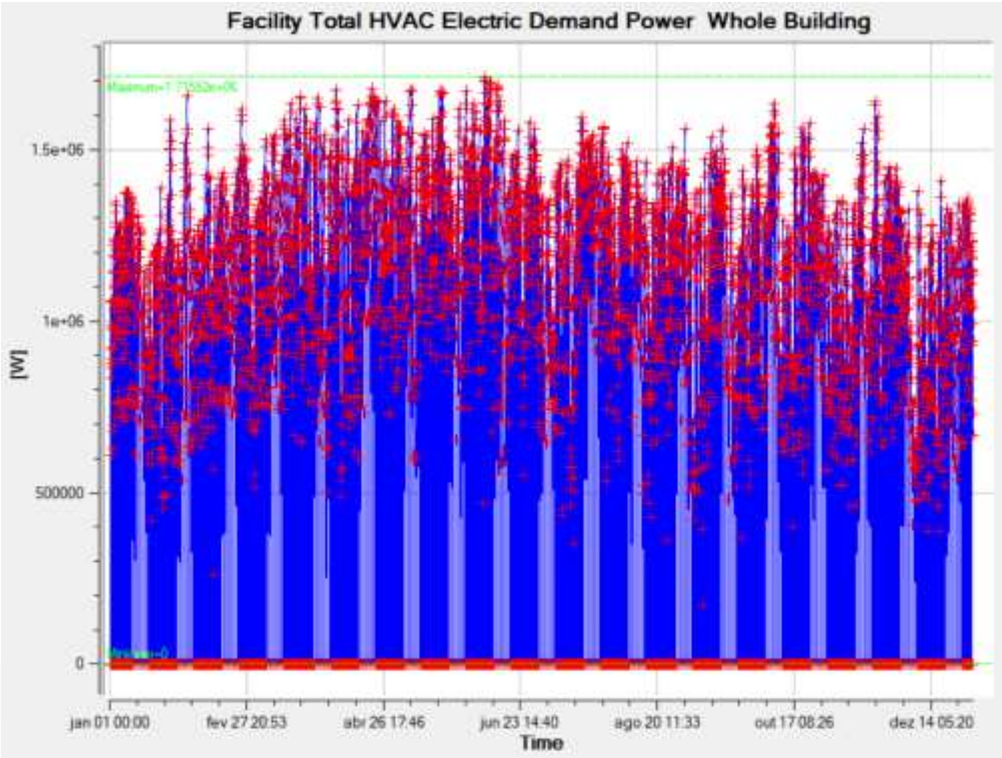

Figure 5 – Singapore mall HVAC electric demand (W)

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. Make-up water to the sanitary use hot water system is assumed to be at 22.2ºC all year. Figure 8 reveals the annual sanitary use hot water energy demand. The mall uses hot water at 45ºC.

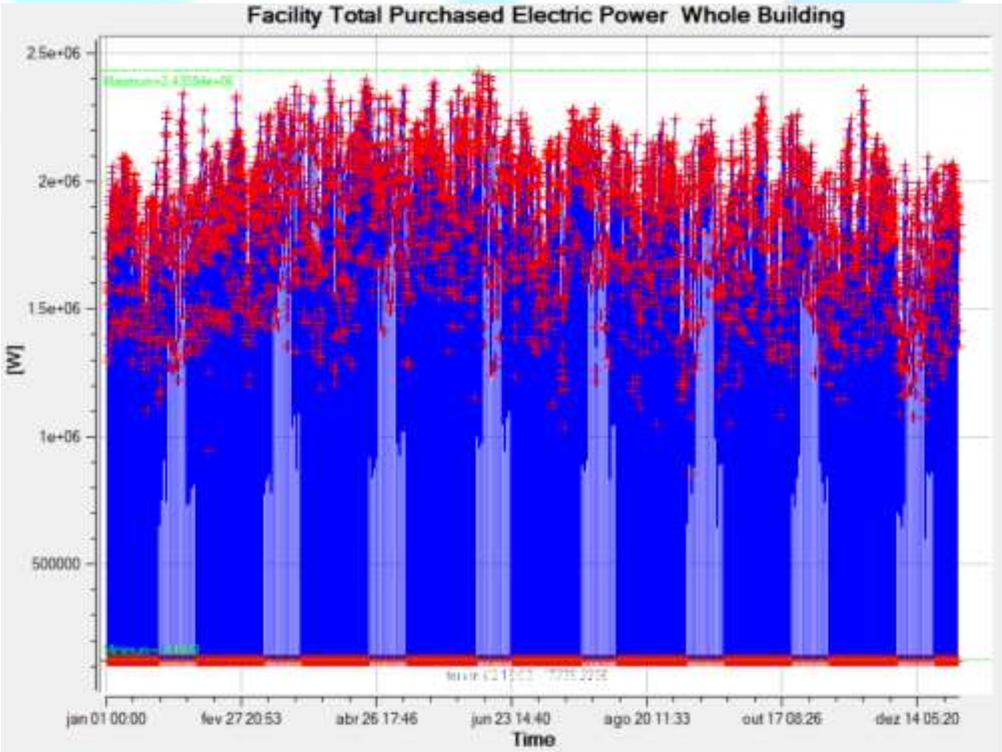

Figure 6 – Singapore mall electricity demand (W)

Annual building energy consumption totalized 541.5 kWh/m^2 per year (no energy conversion efficiency).

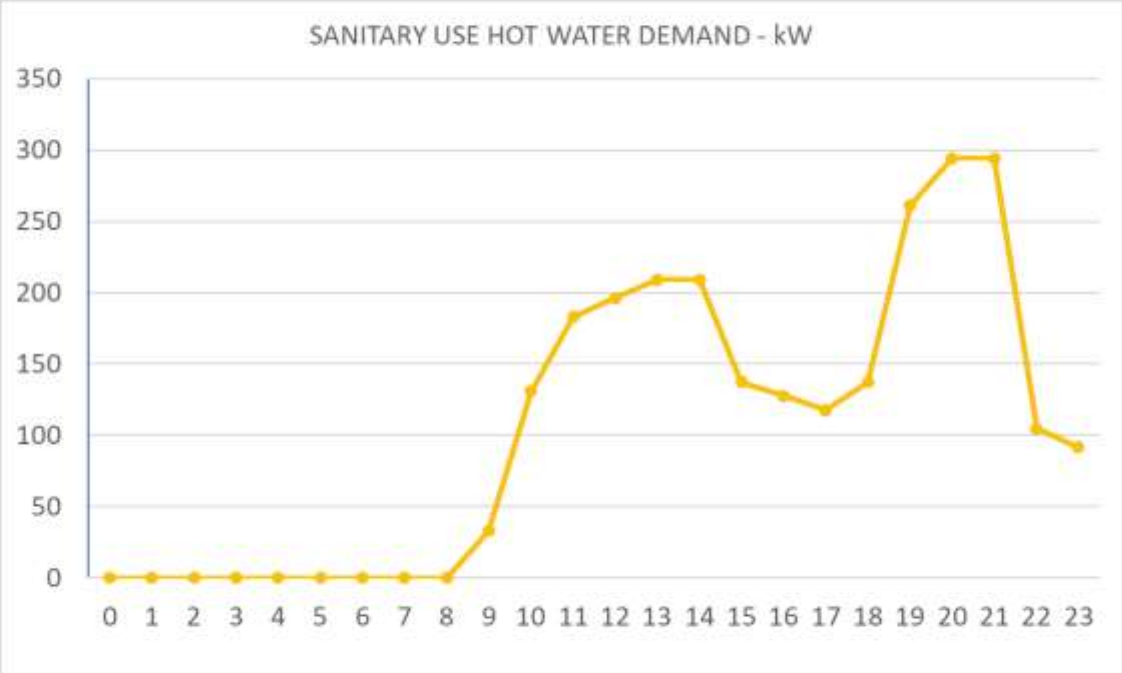

Figure 7 – Singapore mall daily sanitary use hot water demand (kW)

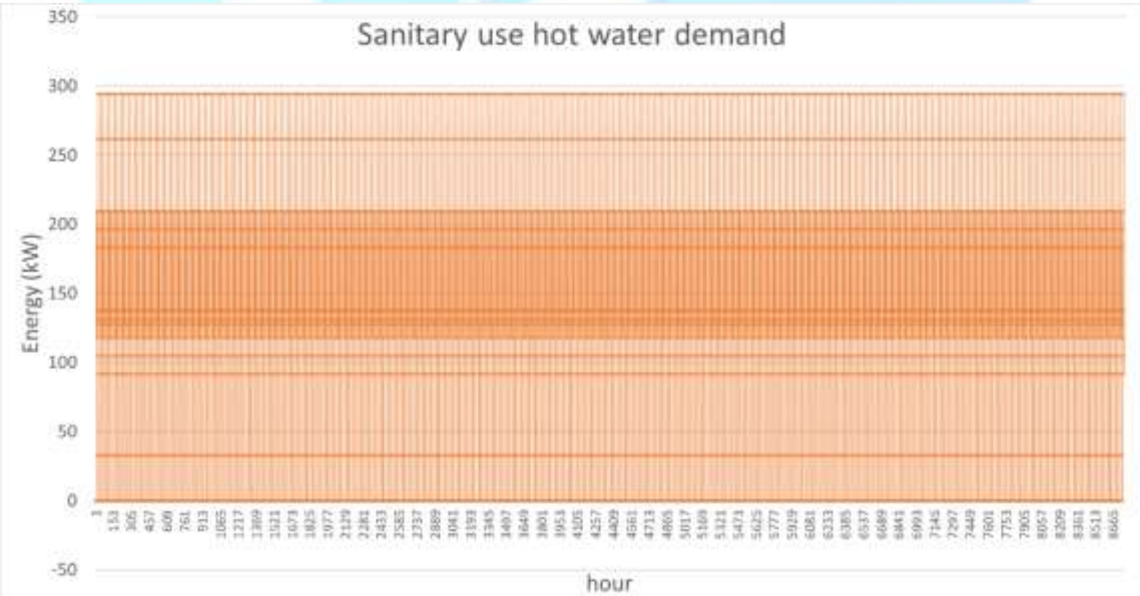

Figure 8 – Singapore mall annual sanitary use hot water demand (kW)

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 an exhaust gases and hot water absorption chiller (double effect), and low-temperature hot water at HE1 and HE2 – sanitary use (flows 12 to 15) – HE2 and HE1 is in a series arrangement.

The engine primary circuit (PC) recovers energy from the engine jacket (flows 7 to 2) and uses it at the low temperature absorption chiller generator. Engine exhaust gases are used directly in the high temperature absorption chiller generator – flows 18 to 20. 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.

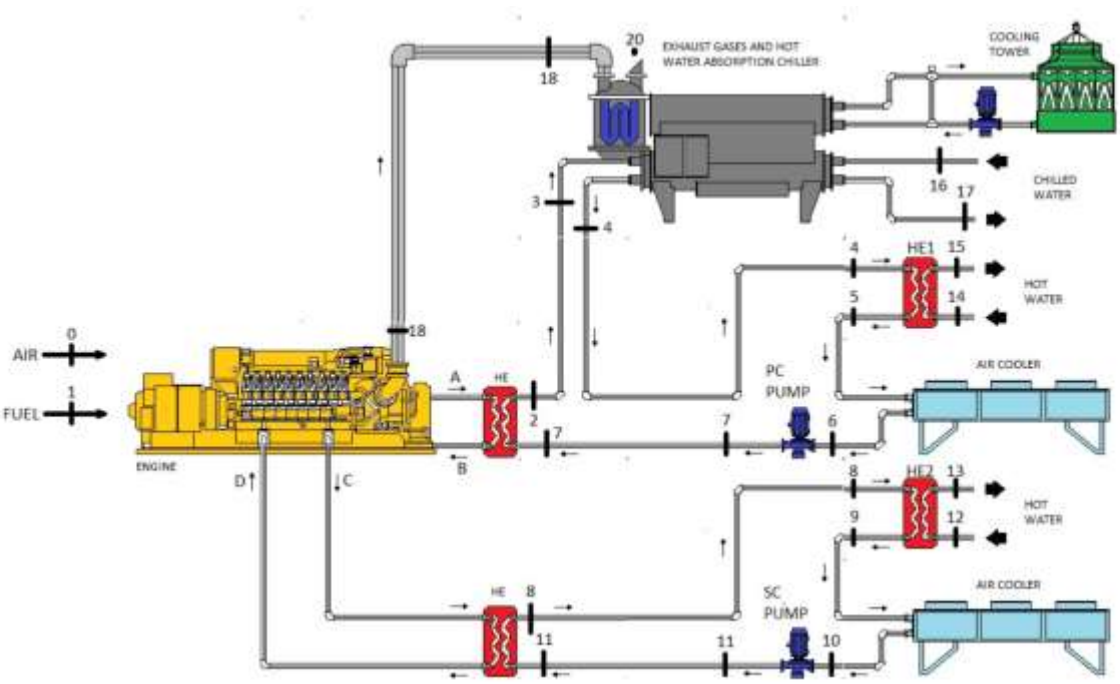

Figure 9 – engine CHP scheme

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	355.69	275	81.60	11.188	341.84	275	81.18	14.680	340.04
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	1.063	93.44	300	22.22	2.011	93.44	300	22.22	2.286	93.44
13	250	35.22	1.063	147.68	250	36.04	2.011	151.12	250	37.41	2.286	156.86
14	250	35.22	1.063	147.68	250	36.04	2.011	151.12	250	37.41	2.286	156.86
15	200	45.00	1.063	188.52	200	45.00	2.011	188.52	200	45.00	2.286	188.52
16	400	13.33	34.297	56.35	400	13.33	44.984	56.35	400	13.33	60.865	56.35
17	300	7.22	34.297	30.64	300	7.22	44.984	30.64	300	7.22	60.865	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	154.84	1.232	445.79	100	154.84	1.814	445.79	100	154.84	2.386	445.79

Table 2 – engine CHP energy balance – summer mode

	800 kW ENERGY		1200 kW ENERGY		1560 kW ENERGY	
	(kW)	(%)	(kW)	(%)	(kW)	(%)
hot water SC	57.66	3.00	116.00	4.20	144.99	4.00
hot water PC	43.41	2.26	75.21	2.72	72.37	1.99
chilled water	881.84	45.86	1156.63	41.83	1564.96	43.14
electricity	784.00	40.77	1176.00	42.53	1528.80	42.14
SUM	1766.92	91.88	2523.84	91.28	3311.12	91.27

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 all cases, the exhaust gases are cooled to 154.84ºC at the high temperature absorption chiller generator (flow 20). At the low temperature generator, hot water energy is recovered between flows 3 to 4 temperatures (table 1).

The absorption chiller is selected to operate with the same condition of the existing centrifugal chillers (i) chilled water between 7 and 12ºC and (ii) cooling tower water between 35 and 29ºC. The absorption chiller COP is assumed as 1.1 at the design condition. COP is calculated using the energy that is effectively used by the absorption machine: [(flow18 – flow20) + (flow3 – flow4)].

Heat exchanges 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 45ºC. HE2 is designed to warm water from 22ºC to 40ºC. HE1 and HE2 are in a series arrangement looking to meet 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.

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 881.8 kW of chilled water at the absorption chiller (45.86%) and 43.41 kW of hot water at HE1 (2.26%). SC energy (57.65 kW - 3%) can be used for low-temperature hot water production. A EUF equal to 91.88% 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). In the summer mode, it can produce 1156.63 kW of chilled water at the absorption chiller (41.83%) and 75.21 kW of hot water at HE1 (2.72%). SC energy (116.0 kW - 4.2%) can be used for low-temperature hot water production. A EUF equal to 91.28% can be reached – table 2.

The 1560 kW engine CHP system produces 1528.8 kW (42.14% electrical efficiency) of net electricity. In the summer mode, it can produce 1564.96 kW of chilled water at the absorption chiller (43. 14%) and 72.37 kW of hot water at HE1 (1.99%). SC energy (144.99 kW - 4%) can be used for low-temperature hot water production. A EUF equal to 91.27% can be reached – table 2.

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

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: two 1200 kW engine CHP systems operating at electrical dispatch.
- Case 5: two 1200 kW engines CHP systems operating at thermal dispatch with 70% minimum EUF.
- Case 6: three 1200 kW engines CHP systems operating at thermal dispatch with 70% minimum EUF.
- Case 7: two 1560 kW engines CHP systems operating at thermal dispatch with 70% minimum EUF.
- Case 8: three 1560 kW engines CHP systems operating at thermal dispatch with 70% minimum EUF.

Table 3 – General Results

		CASE 1	CASE 2	CASE 3	CASE 4	CASE 5	CASE 6	CASE 7	CASE 8
		800FL	1200FL	1560FL	1200NEO2ED	1200NEO2TD70	1200NE03TD70	1560NEO2TD70	1560NEO3TD70
	ELECTRICITY								
1	electricity consumption (kWh/year) =	10,566,945.36	10,566,945.36	10,566,945.36	10,566,945.36	10,566,945.36	10,566,945.36	10,566,945.36	10,566,945.36
2	electricity production (kWh/year) =	4,305,670.87	6,458,506.30	8,396,058.25	8,744,062.67	12,914,012.58	19,355,358.85	16,782,319.51	25,075,814.21
3	electricity production - net (kWh/year) =	4,219,557.45	6,329,336.36	8,228,137.18	8,572,560.73	12,655,732.37	18,968,251.83	16,446,673.15	24,574,297.88
4	avoided electricity abs chiller (KWh/year) =	771,970.46	1,017,600.66	1,378,544.96	1,587,626.32	2,033,701.65	3,042,065.99	2,760,211.81	4,017,321.23
5	aditional electricity (kWh/year) =	5,575,417.46	3,220,008.35	960,263.23	406,758.31	-4,122,488.66	-11,443,372.46	-8,639,939.60	-18,024,673.75
6	engine fuel consumption (kWh/year) =	10,345,197.47	14,867,649.81	19,543,898.27	21,081,637.42	29,728,760.77	44,560,447.65	39,066,370.25	58,389,521.79
	HOT WATER								
7	Hot water consumption SC (kWh/year) =	922,034.16	922,034.16	922,034.16	922,034.16	922,034.16	922,034.16	922,034.16	922,034.16
8	Hot water production PC (kWh/year) =	199,188.80	277,655.54	234,608.77	13,014.81	153,497.95	84,085.08	55,875.25	45,376.77
9	Hot water production SC (kWh/year) =	280,073.27	489,573.93	584,346.76	626,702.36	768,525.50	837,873.38	866,131.84	876,184.01
10	aditional hot water SC+PC (kWh/year) =	442,772.10	154,804.70	103,078.63	282,317.00	10.71	75.71	27.08	473.39
	CHILLED WATER								
11	Chilled water demand (RT) =	9,563,391.94	9,563,391.94	9,563,391.94	9,563,391.94	9,563,391.94	9,563,391.94	9,563,391.94	9,563,391.94
12	chilled water production (RT) =	1,330,983.58	1,754,483.82	2,376,801.77	2,737,286.76	3,506,381.72	5,244,941.10	4,758,985.97	6,926,416.07
13	cooling load attended	13.92%	18.35%	24.85%	28.62%	36.66%	54.84%	49.76%	72.43%
	EUF, ENGINE LOAD AND PAYBACK								
14	EUF	90.67	89.24	89.07	89.36	87.16	86.03	87.30	85.36
15	ENGINE LOAD	100.00	100.00	100.00	69.30	99.98	99.91	99.96	99.63
16	PAYBACK	1.95	2.02	2.02	2.94	2.04	2.05	2.03	2.06
	COMPLETE PES								
17	PEC without cog/trig (kWh/year) =	24,484,311.86	24,484,311.86	24,484,311.86	24,484,311.86	24,484,311.86	24,484,311.86	24,484,311.86	24,484,311.86
18	PEC with cog/trig (kWh/year) =	23,187,993.92	22,175,148.98	21,784,985.40	22,290,346.87	20,653,729.33	19,668,240.42	20,203,575.90	19,393,122.92
19	PES (%) =	5.29	9.43	11.02	8.96	15.65	19.67	17.48	20.79
	EUROPEAN UNION DIRECTIVE - PES								
20	PES EU Directive (no grid loss - 53%) (%) =	23.77	23.69	23.36	22.87	22.35	21.61	22.22	20.93
21	PES < 0.45 kV (%)=	30.87	31.09	30.74	30.11	29.66	28.49	29.10	27.60
22	PES < 12 kV (%) =	28.87	29.01	28.67	28.08	27.62	26.57	27.18	25.75
	EQUIVALENT THERMAL EFFICIENCY								
23	ETE (no grid loss) =	50.87%	52.42%	51.55%	49.88%	51.18%	50.56%	50.49%	49.84%
24	ETE (10% grid loss) =	56.52%	58.25%	57.28%	55.42%	56.86%	56.17%	56.10%	55.38%
25	ETE (20% grid loss) =	63.59%	65.53%	64.44%	62.35%	63.97%	63.20%	63.11%	62.30%

Results Discussion

Table 3 reveals the engine CHP cases main results.

Line 1 reveals the mall annual electricity consumption (kWh/year), calculated using figure 6 data (EnergyPlus results). At the hours the mall is closed (engine CHP system is off) an average demand of 128 kW was calculated, resulting in a daily and annual consumption of 1024 kWh/day and 373.760 kWh/year, respectively. This consumption represents only 3.5% of the building annual electricity consumption.

Line 2 reveals the CHP cases annual power production (kWh/year). Cases 1, 2, 3, and 4 produces less electricity than the mall consumption, and additional electricity is bought from the grid. Electricity production is close to 43% (case1), 66% (case 2), 89% (case 3), and 95% (case 4) when compared to the annual corrected electricity consumption (uses the avoided electricity consumption in the absorption chiller). Cases 5, 6, 7, and 8 export electricity to the grid, case 5 exports 48%, case 6 152%, case 7 close to 110%, and case 8 to 275% of the mall corrected 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 12 reveals the annual absorption production

(RT/year – Refrigeration Tons). Line 4 results are equal line 12 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 low temperature hot water (bathrooms and kitchen use) energy consumption (kWh/year) – sanitary use hot water (figure 8).

Line 8 and 9 reveals the engine CHP hot water production (kWh/year), line 8 is the PC energy recovery (HE1) and line 9 is the SC energy recovery (HE2). HE 2 and HE1 are in a series arrangement. Line 10 reveals the surplus hot water production.

Line 11 reveals the annual cooling load (RT/year) – figure 5 cooling load converted to RT (EnergyPLus results). Line 12 reveals the engine CHP cases annual chilled water production (RT/year). Line 13 reveals the percentage of the cooling load that is met by cases 1 to 8, case 1 supplies 13.92% while case 8 supplies 72.43% of the mall cooling load.

Line 14 reveals the average annual EUF (Energy Utilization Factor). Case 1, 2, 3 and 4 revealed the higher values, 90.67%, 89.24%, 89.07% and 89.36% respectively. Cases 5, 6, 7, and 8 revealed an average EUF between 85.3% and 87.3%. 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 15 reveals the engine CHP cases average engine load. Excluding case 4 that operates at electrical dispatch, all cases revealed an engine load equal or close to 100%. Equatorial buildings cooling load is very constant in the whole year and the proposed cases don't meet all the cooling load.

Line 16 reveals the payback scenario. The economic scenario assumed 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. All cases revealed a payback scenario close to 2 years excluding case 4 that revealed a 3 years payback.

Line 17 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 18 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 45.1% and is exported to the grid assuming an avoided electrical production with 45.4-46.2% thermal efficiency (it depends on the site electricity use and exported electricity percentage). 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 is met. Line 19 reveals the PES between 5.29% and 20.79% - equation 16. Better cases are the ones that export more electricity to the grid while matching most of the thermal loads – case 8 revealed the higher PES.

Line 20 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 20.93% (case 8) and 23.774% (case 1) was calculated.

Using the EU directive reviewed harmonized reference efficiency values (avoided grid loss factors) the PES is recalculated on line 21 (connection with the grid at a voltage lower than 450V) and line 22 (connection with the grid at a voltage higher equal than 450V and lower than 12000 V). The results follow the line 21 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 45.1-46.2% at lower than 450V connection and 47.2-48% at lower than 12000V.

ETE (equivalent thermal efficiency) is revealed in lines 23 to 25. At line 23 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) when grid loss is assumed. ETE between 49.84% (case 8 no grid loss) and 65.53% (case 2 with 20% grid loss) were calculated.

A detailed look on case 8

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 8. The NEO values are represented by the brown lines. The engine CHP case 8 system doesn't operate for 3285 hours/year (night period when the mall is closed). For 2 hours only one engine operates, for 8 hours two engines operate and for 5465 hours three engines are in operation. The blue lines represent the EUF (divided by 100). Lower cooling loads (figure 5) reduces the engine load and the NEO value, allowing the system to operate with high efficiency in most of the operation hours (see dots in figure 10). NEO equal to 1 and 2 are directly associated with low cooling loads (HVAC electrical demand) revealed in figure 5.

This same analysis was revealed by COGMCI software for cases 5 to 7 (figures not shown).

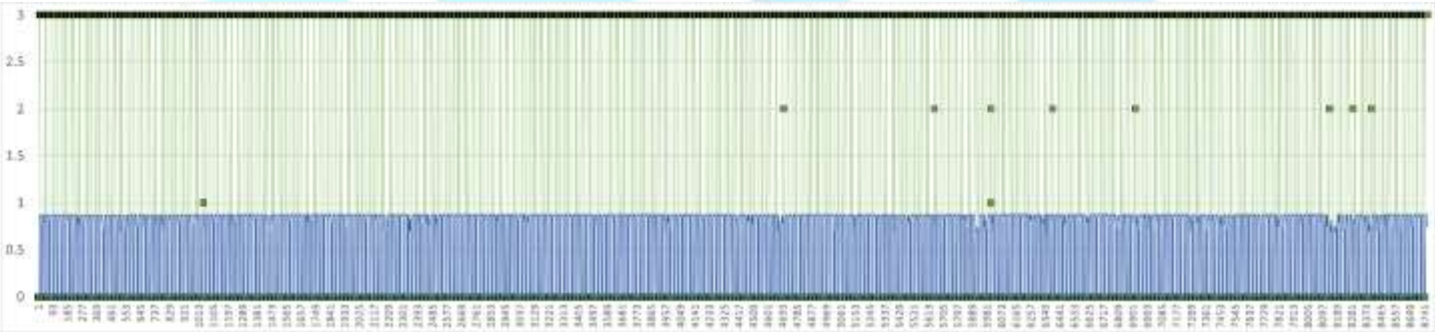

Figure 10 – case 8 number of engines operating and EUF/100

Conclusions

The EnergyPLus software was used to predict the building electrical and cooling load on an annual basis. When evaluating existing buildings a "refine" can be done adjusting the model to the existing data (gas and electrical bills, existing equipment, measured data, existing benchmark, 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.

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. Site energy demands also affect the results (sanitary use hot water, cooling, and electrical demands). A detailed discussion of the results requires a detailed analysis of COGMCI results – not revealed here.

Buildings located at equatorial cities usually don´t need space heating and a high cooling load is verified. In this case, no heating is necessary. Air conditioning (cooling) can represent more than 50% of the building electricity consumption, total building power consumption and air conditioning power consumption can be evaluated comparing figures 5 and 6.

The system's performance was 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.

The energy utilization factor (EUF) reveals the engine CHP energy that is being used. In this case study it is higher for an electrical base load system (case 1) since (i) at base load unused residual energy is minimized and (ii) the engine used in case 1 and the thermodynamics design data has the higher EUF (table 2).

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 8), in fact using the EU directive case 1 has the better result. The EU directive calculating the power plants thermal efficiency assuming grid losses look to be adequate 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 engine cog/trigeneration system. That’s why a 5% PES is calculated for a small system (case 1) and a 20% PES is obtained for a bigger system (cases 6 and 8).

ETE indicates how efficient needs to be the country average thermal efficiency to disregard the benefits of engine CHP systems. ETE results indicate that engine CHP is the best available technology for some applications. ETE between 49.84% and 52.42% is achieved when disregarding grid losses. Adopting a 20% grid loss scenario ETE is between 62.3% and 65.53%. No countries have average thermal efficiency compared to this.

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.

In this case, since the cooling load is almost constant through the whole year, the oversized solutions (able to export electricity to the grid) meets more cooling load (line 13 table 3) while operating at a very similar engine load (line 15 of table 3) – they almost operate all full load all the time. Figure 10 revealed that case 8 operates less than 3 engines at only 10 hours per year with an average engine load of 99.64%. As previously discussed, PES is higher for oversized systems (cases 5 to 8).

COGMCI is formed by several mathematical models to design and simulate engine CHP equipment and systems. In this case study an “exhaust gas and hot water absorption chiller” is evaluated. Absorption chiller manufacturers designed their equipment looking to a high efficiency and a reliable operation. COGMCI team notes that exhaust gas temperature leaving the absorption chiller will be different (flow number 20) for different manufacturers. Exhaust gas flow passes into the high stage generator and hot water into the low stage generator. Some manufacturers also recover exhaust gas energy in heat exchangers used to warm the solution (water and lithium bromide) going back to the generator. The amount of energy being supplied by the exhaust gas and by the hot water also affects the COP. It’s difficult to create a model that uses all the manufacturers particular design conditions and part load strategy. At COGMCI different absorption chiller performance can be adjusted using the defined absorption chiller COP. COGMCI developers suggest you adjust the COP input of the absorption chiller to meet the cooling capacity defined by your absorption chiller supplier.

A given site with coincident thermal and electrical loads have a CHP potential to reduce CO_2 emissions. Basic analysis does not reveal 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 and the site existing equipment performance.

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 – efficiency is directly connected with CO_2 emissions. Not all the time the better technical solution does 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 and the lower payback solution).

The scenario used for comparison in this study can be intended as a high efficiency scenario, since (i) the average thermal plant efficiency is 53% disregarding grid losses and 45% when assuming grid losses – IEA studies reveals this is a very high value, (ii) hot water is produced at fuelled hot water boilers with 92% efficiency and (iii) electrical chillers with a COP equal to 6 (0.58kW/RT) are used. Most of the countries and real installations face a less efficient scenario. But even at this high efficiency scenario a 20% primary energy savings (CO_2 emission reduction) is predicted.

Figure 11 reveals a smart grid layout. Grid operator must maintain its stability supplying electricity with low risk technologies with lower CO_2 emission for their customers. As renewables are integrated into the electrical system, the higher CO_2 emission power plants should operate at less annual hours. Engine CHP can contribute to the grid flexibility, reliability, stability, and resilience while reducing CO_2 emissions. In a 100% renewable grid scenario engine CHP can be fuelled by clean fuels with a high efficiency operation.

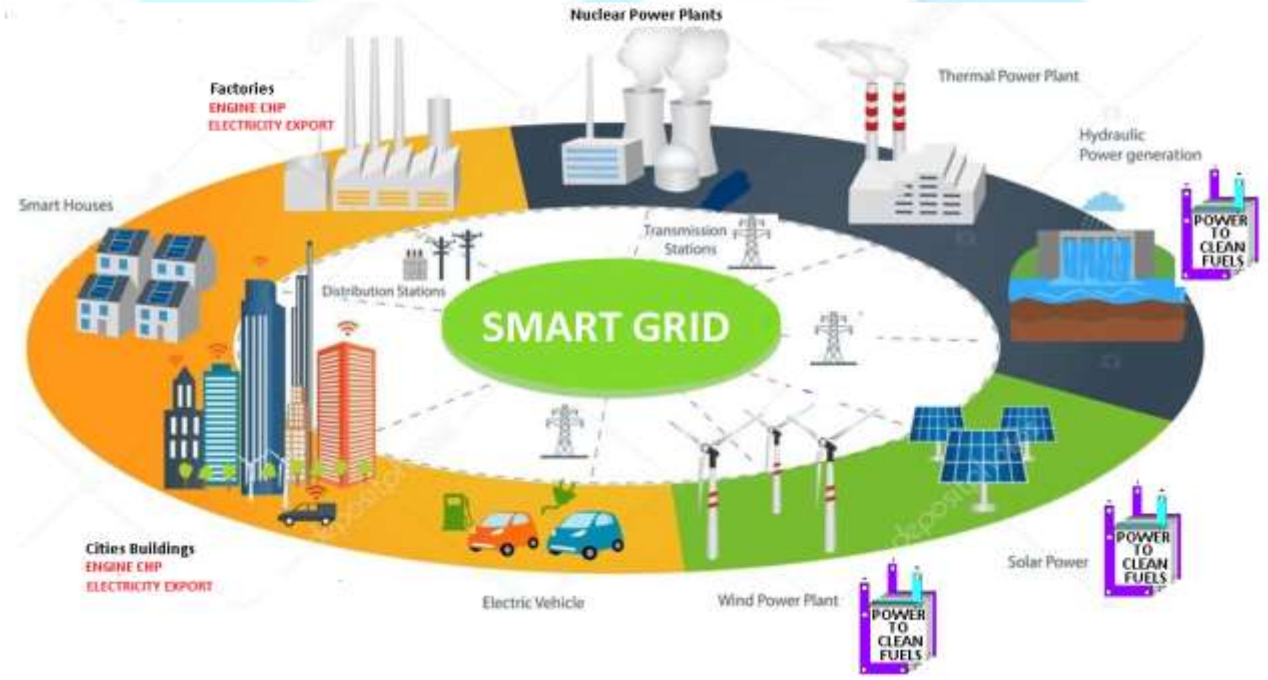

Figure 11 – smart grid layout

ANNEX I – EQUIVALENT THERMAL EFFICIENCY CALCULATION

$$EUF = \frac{\dot{W}_{net}+\dot{m}_{14}(h_{15}-h_{14})+\dot{m}_{12}(h_{13}-h_{12})+\dot{m}_{16}(h_{16}-h_{17})}{\dot{m}_1.h_1} \qquad [1]$$

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

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

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

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

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

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

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

Trigeneration energy consumption can be calculated as:

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

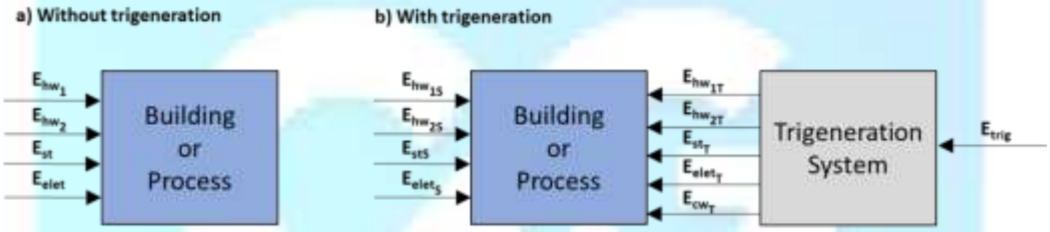

Figure 13 – building/process energy consumption

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

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

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

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

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

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

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

ANNEX II – PES – EU DIRECTIVE

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

19.12.2015 EN Official Journal of the European Union

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.. 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		

L 333/58 EN Official Journal of the European Union 19.12.2015

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

19.12.2015 EN Official Journal of the European Union L 333/61

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

REFERENCES

[1] Espirito Santo D.B., COGMC Internal Combustion Engine Cogeneration Software Evaluator – accessed 07/21/2020 –. https://www.sisterm.com.br/en/cogeneration

[2] EnergyPlus – DOE USA – accessed 03/25/2020 - https://energyplus.net/

[3] Directive 2012/27/EU of the European Parliament and of the Council, October 2012 – accessed 03/28/2020 - https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2012:315:0001:0056:en:PDF

[4] Official Journal of the European Union. COMMISSION DELEGATED REGULATION (EU) 2015/2402 of 12 October 2015; https://eur-lex.europa.eu/eli/reg_del/2015/2402/oj; 2020 [accessed 03/30/2020].