Evaluating an Oversized Engine Trigeneration System Operating at Thermal Dispatch using the Equivalent Thermal Efficiency Criteria

Denilson Boschiero do Espirito Santo and Flavio Fernando Guarinello Junior

Cogeneration/trigeneration can contribute to reduce CO2 emissions in the transition from fossil fuels to renewables, decentralizing the electricity production, producing high efficiency electricity and recovering prime mover residual energy to attend local heating and/or cooling loads. The comparison between cog/trigeneration systems and centralized thermal plants and local heat/cool production should be made by comparing the energetic value of their products and their energy conversion efficiencies. In this paper a typical hotel building located at a temperate climate was chosen as a case study due to the occurrence of peak and intermediate heating and cooling loads. The annual assessment is performed by running the software COGMCI with different operational strategies with a special focus in the thermal dispatch mode. An oversized engine able to export electricity to the grid, contributing to the grid stability, is used as the prime mover. The Energy Utilization Factor (EUF), the Equivalent Thermal Efficiency (ETE) defined in this paper, the Primary Energy Savings (PES) using a European directive and the Exergy Efficiency are used to evaluate the system performance. EUF between 66.2 and 73.6%, ETE between 51.6 and 60.4%, PES between 10.5 and 15.6%, exergy efficiency between 35.8 and 37.8% were calculated.

Keywords: trigeneration, EUF, exergy efficiency, PES, ETE, simulation

1. INTRODUCTION

The efficient use of natural resources can contribute to reducing the environmental impact of human activities. In the electricity generation field, the use of renewable technologies should be prioritized. While several renewable technologies are available, solar (photovoltaic) and wind turbines have a higher potential and are actually rising their participation in the electricity generation share [01]. Photovoltaic could make up 24% of the global installed capacity by 2040 [02]. Wind turbines are expected to contribute with 20.4% of the total gross capacity additions in the world by 2040 [01]. Due to their intermittent characteristics, other technologies are being proposed to contribute to a stabilized electric grid while also promoting reduced environmental impact (CO_2 emission).

According to IEA energy efficiency improvements is the primary choice in many regions due to its cost-effectiveness to reduce or mitigate the CO_2 emissions from the electricity generation industry [03] – figure 1.

Cog/trigeneration has been applied as an energy efficiency technology by (i) producing high efficiency electricity, (ii) recovering prime mover residual energy and (iii) reducing grid transmission losses (decentralized electricity).

Several methods and approaches are found in the literature where the purpose encompasses design parameters and analysis with many evaluation criteria related to energy, exergy, economic and environmental issues. Fardoun et al [04] and Jradi et al [05] developed a review of cog/trigeneration systems design, configurations, prime movers, cooling technologies, etc,

Depending on the energy flows produced by the cogeneration plant it can be referenced as trigeneration or poligeneration.

Cog/trigeneration systems had also be evaluated and designed to operate as a renewable source. Safaei et al [06] evaluated a cogeneration model integrated with solar thermal (hot water) and photovoltaic.

Engine cog/trigeneration systems can also operate as a renewable source when using biofuels [07] or hydrogen. Wang et al [08] did an experimental study converting a diesel 6.5 kW engine to hydrogen, efficiencies between 57 to 82% were obtained, depending on the engine load. They verified an equivalent engine performance with diesel and hydrogen.

When using fossil fuels cogeneration/trigeneration systems needs to be designed and planned as a high efficiency solution, contributing to reduce countries CO_2 emissions when compared with site heat production and centralized electricity production.

Simulation [09] and optimization methods can be used to evaluate the system performance and to optimize constraints [10], looking to design high efficiency systems. Franco and Versace [11] developed a composite indicator to evaluate the benefits of CHP for district heating.

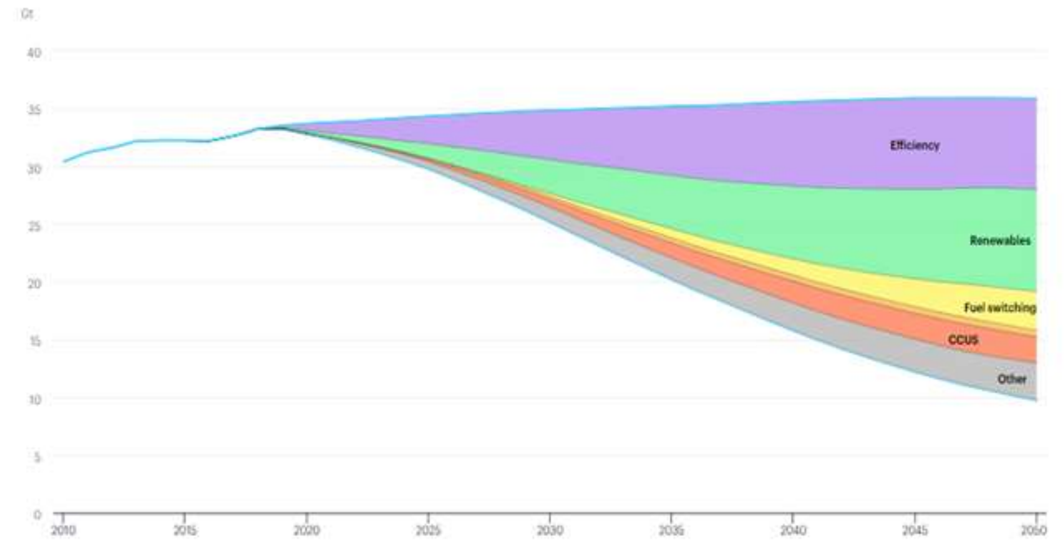

Figure 1 - Stated Policies Scenario, 2010-2050. IEG – World Energy Outlook 2019 [03]

Angrissani et al [12] evaluated the performance of small scales cog/trigeneration systems considering efficiency, emission factor, and unitary price of electricity and natural gas of some European countries. They concluded that small scale cog/trigeneration is more convenient for countries in which electricity production is mainly based on fossil fuels.

Buildings and processe- have variable energy loads with uncoincidental energy demands, thermal energy storage (TES) can improve the system overall efficiency [13]. Serra et al [14] discussed the TES using thermoeconomic analysis, they analyzed a 24-hour profile and traced the discharged energy flow back to its production period to calculate hour energy recovery. Gvozdenac et al [15] evaluated the performance of a monitored gas turbine combined cycle cogeneration system revealing their variable loads and annual performance.

Organic Rankine cycle (ORC) can also be used to recover engine low temperature energy, Villarini et al [16] evaluated the performance of a solar ORC trigeneration system.

Both thermal and electricity demand rarely are met by the trigeneration capacity and then, supplementary generation requires to be provided by complementary systems, being already in place (existing) or not. Ahn et al [17] evaluated a CCHP hybrid chilled water system composed of an absorption chiller and an electrical chiller.

Another important factor when evaluating cog/trigeneration system is the operational mode [18-22]. Cho et al [18] discussed some strategies related to follow the energy needs (electricity or thermal) and base load. Espirito Santo evaluated an engine trigeneration system operating at base load [20] and electrical dispatch and full load [21].

A hybrid operational approach has been analyzed by [19] where the goal is to set a prime mover size to run at part load condition focusing on minimizing any excess of electricity and heat production in various climate zones of the USA

Economical dispatch is being explored by the researchers aiming to control the entire system based on the weather forecast and fuel and electricity prices daily operation [22-23].

The challenge is to find out a balance between approaches that use the variables involved in the main goal: (i) to meet or not all the electric and thermal demand, (ii) design a system to obtain the highest profitability or (iii) include the mitigation of CO2 emissions into the context. Thus, it is a matter of balancing the goal of all stakeholders involved.

In terms of the designing process of a trigeneration system for a building or process, some steps need to be done and define which size fits better to demand profiles throughout the year and following the project goals. For building the design is quite dependent upon the climate conditions and seasonal conditions, since they set out how the thermal and electrical demands behave. Also, the operating strategy should be chosen and all available and known criteria weighted to each other. A balance of cost savings, energy savings, and consumption, as well as environmental emissions, should be part of the analysis [04].

Among this complex scenario, this paper aims to reveal some aspects that were underexplored by previous studies.

To evaluate engine cog/trigeneration system performance a new indicator is defined: equivalent thermal efficiency (ETE) [25]. ETE is defined using the PEC analysis with and without a cog/trigeneration system. Espirito Santo is using PES since 2010 [20] and compared the PES analysis with the exergy destruction analysis in a previous paper [26].

A new interpretation of thermal dispatch is defined at this paper, considering an engine trigeneration system producing (i) low temperature hot water (sanitary use), (ii) medium temperature hot water (space heating), (iii) chilled water (space cooling) and (iv) electricity.

An oversized engine is proposed for the analyzed hotel building. The results reveal that the oversized engine can export electricity to the grid at low renewables production hours and/or grid peak hours contributing to the electrical grid stability while rising countries average thermal efficiency.

The software COGMCI developed by Espirito Santo [27] is used to develop the engine cog/trigeneration analysis. EnergyPlus software [28] is used to build the energy loads profiles.

2. CASE STUDY

The hotel building modeled in this case study is shown in figure 2. The hotel building is assumed to be located in Vienna Austria. The building has a total area of 13,400 m^2 and a conditioned (temperature is controlled) area of 11,800 m^2. The building has 2 towers with 10 floors each where the rooms are located and a 3 floor base where car park (underground), lobby, restaurant, kitchen and guest services are located. The building is modeled by 35 thermal zones including rooms, lobby, kitchen, corridors, restaurant, stairs, etc. Walls, roofs and windows were defined as typical materials utilized in new constructions in a temperate climate, the global heat transfer coefficient for the walls, roofs and windows are U_{wall} = 0.278 W/m^2.K, U_{roof} = 0.261 W/m^2.K and U_{window} = 2.7 W/m^2.K respectively. Inside design temperature is defined as 24ºC for the summer and as 22ºC for the winter. The hotel is assumed to have an average occupancy of 75% and profiles of energy use for each thermal zone (lights, occupancy, equipment, etc) were inserted in the model trying to approximate a real hotel building energy consumption.

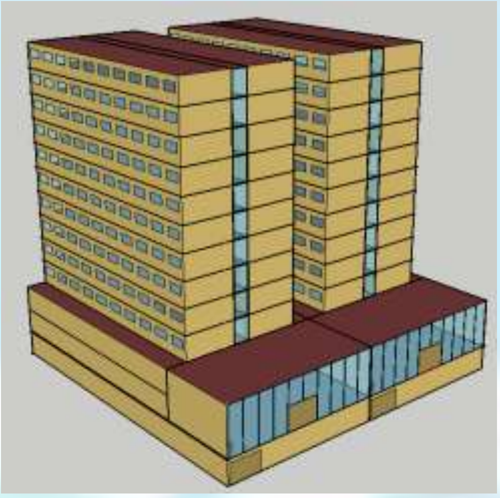

Figure 2 –Hypothetical hotel building utilized in the analysis

3. HOTEL BUILDING ENERGY LOADS AND SYSTEMS

The hotel building is assumed to purchase electricity from the public grid. Its cooling load is supplied by electrical chillers with chilled water temperatures from 7.2ºC (inlet) to 13.3ºC (outlet), a COP of 4.4 is defined. The space heating load is assumed to be met by fueled hot water boilers (90% efficiency) operating from 50ºC (inlet) and 80ºC (outlet). Fan coils run either heating or cooling building spaces as necessary. The hot water for sanitary use is produced by fueled boilers (90% efficiency) supplying hot water at 40ºC, makeup water varies from 10 to 20ºC depending on the season.

Figure 3 reveals the monthly average dry bulb temperature and relative humidity profiles obtained from an EnergyPlus weather file.

Figure 4 reveals the hotel average electricity demand for the different months of the year, the electricity demand profiles of figure 4 includes the electricity consumption in the electrical chillers. Figure 5 reveals the heating load (space heating), figure 6 reveals the cooling load and figure 7 reveals the sanitary use hot water energy assuming 100 liters/day consumption per person.

To simplify the data results discussion, the seasons are treated as winter (December, January and February), spring (March, April and May), summer (June, July and August) and autumn (September, October and November).

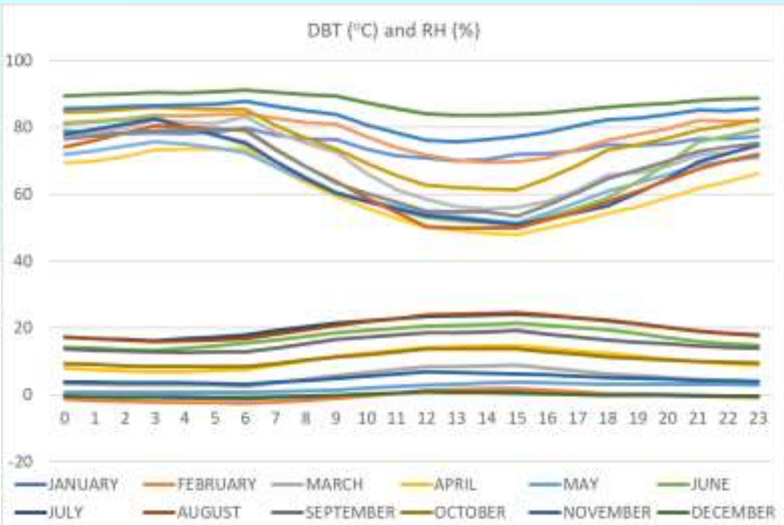

Figure 3 – local average dry bulb temperature (ºC) and relative humidity (%)

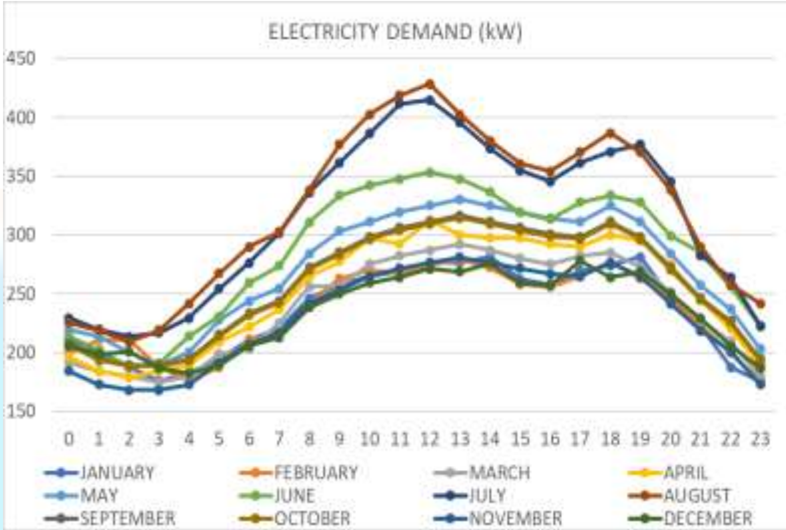

Figure 4 – hotel building electricity demand (kW)

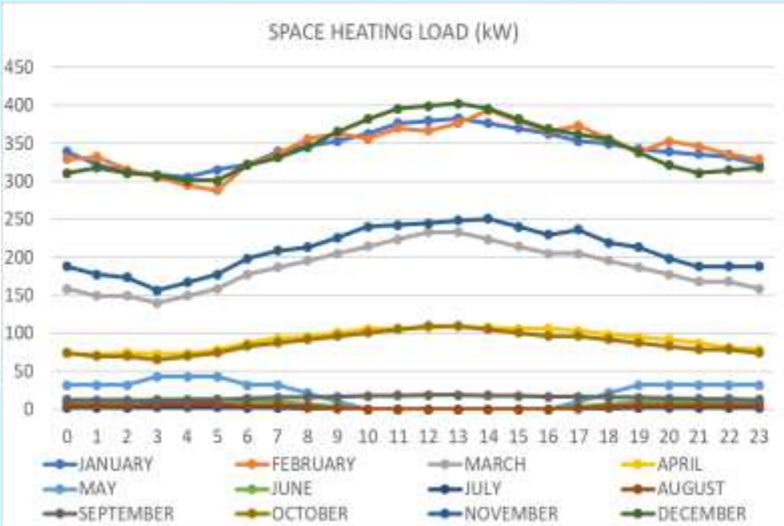

Figure 5 – hotel building heating load (kW)

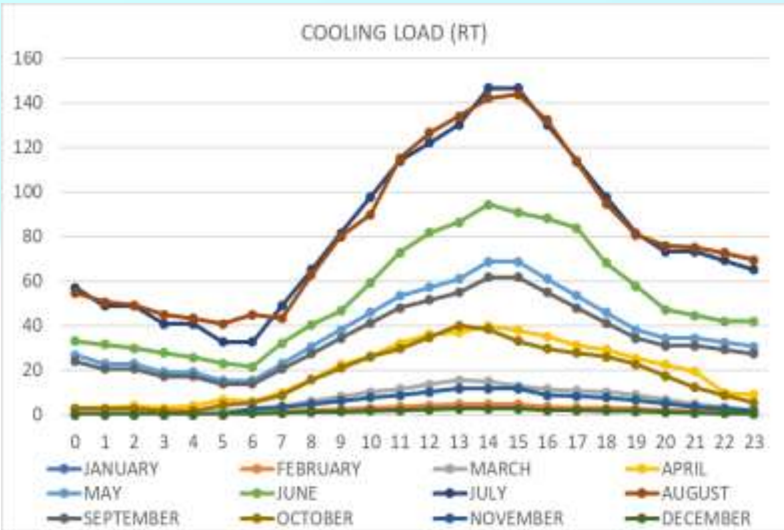

Figure 6 – hotel building cooling load (refrigeration tons)

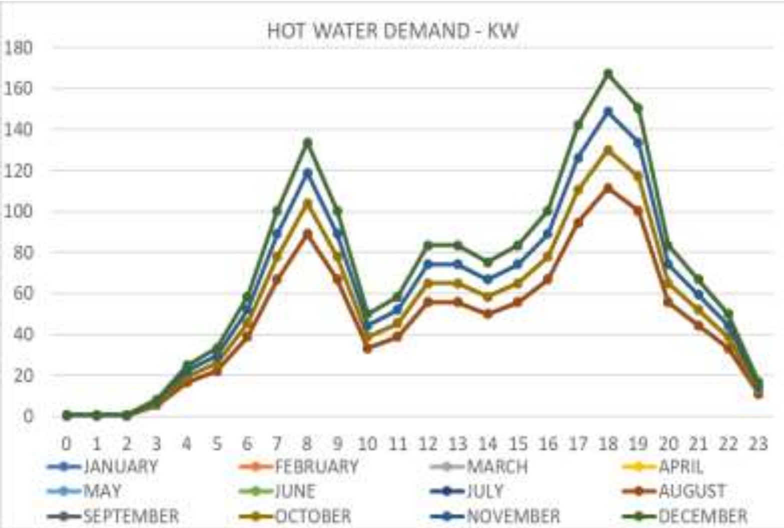

Figure 7 – hotel building sanitary use hot water demand

4. THE TRIGENERATION SYSTEM

Figure 8 reveals the trigeneration system that is proposed to attend the hotel energy demands. The system is formed by a 400 kW engine [29], an exhaust gas heat exchanger (EGHE), an absorption chiller, a heat exchanger (HE1) for space heating hot water and a heat exchanger (HE2) for sanitary use hot water. The absorption chiller is water cooled and a cooling tower is used to reject the absorber and the condenser energy. Air coolers are used to reject engine primary circuit (PC - jacket water) and secondary circuit (SC - intercooler) energy.

The PC hot water system is defined as the water recovering energy from the engine jacket and the engine exhaust gases (flows 2 to 7). The SC hot water system is defined as recovering energy from the engine intercooler (flows 8 to 11), both are constant flows.

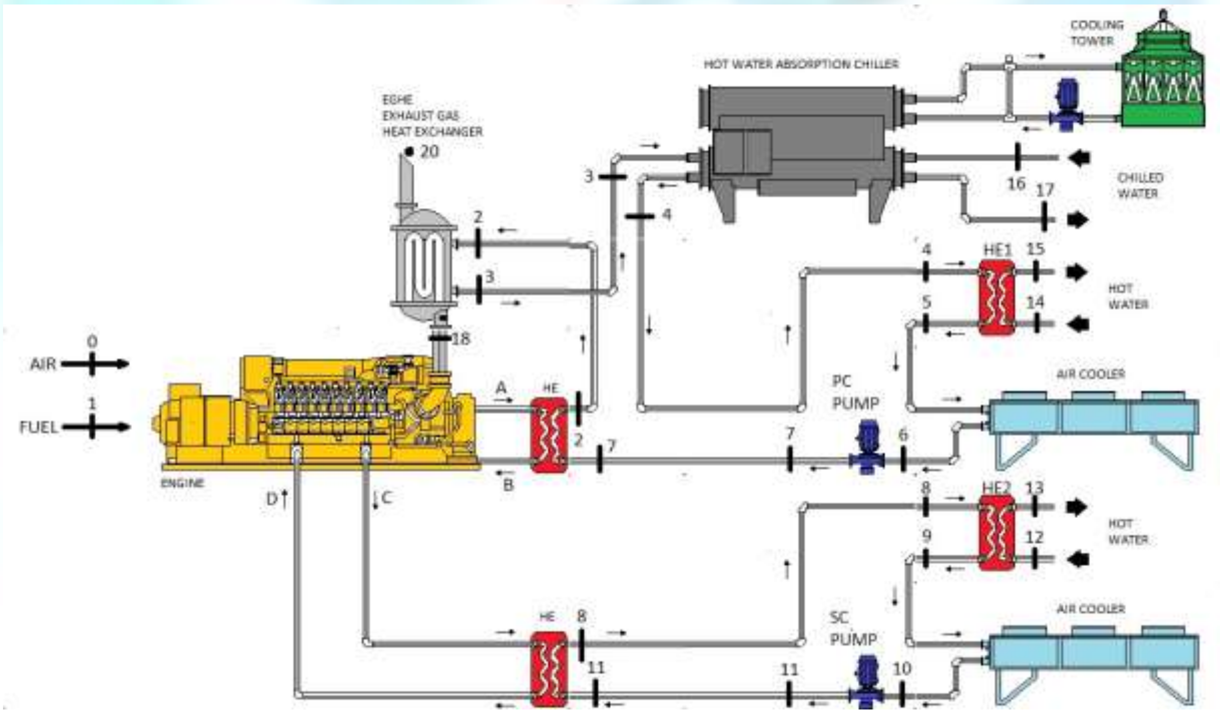

Figure 8 – trigeneration scheme

Table 1 – trigeneration scheme thermodynamics properties – summer mode

flow number	pressure (kPa)	temperature (oC)	mass flow (kg/s)	enthalpy (kJ/kg)	entropy (kJ/kg.K)
0	100.000	25.000	0.600	298.800	5.699
1	100.000	25.000	0.021	45,461.995	0.000
2	425.000	92.220	5.381	386.557	1.218
3	350.000	104.635	5.381	438.806	1.359
4	275.000	84.639	5.381	354.576	1.130
5	200.000	83.889	5.381	351.367	1.121
6	200.000	83.889	5.381	351.367	1.121
7	500.000	83.889	5.381	351.606	1.121
8	275.000	43.889	1.665	183.944	0.624
9	150.000	40.000	1.665	167.582	0.572
10	150.000	40.000	1.665	167.582	0.572
11	400.000	40.000	1.665	167.806	0.572
12	300.000	10.000	0.216	42.290	0.151
13	250.000	40.000	0.216	167.671	0.572
14	250.000	50.000	0.135	209.465	0.703
15	200.000	80.000	0.135	335.042	1.075
16	400.000	13.333	14.217	56.352	0.200
17	300.000	7.222	14.217	30.640	0.110
18	102.000	494.000	0.621	872.858	8.047
19	102.000	494.000	0.621	872.858	8.047
20	100.000	108.887	0.621	415.694	7.224

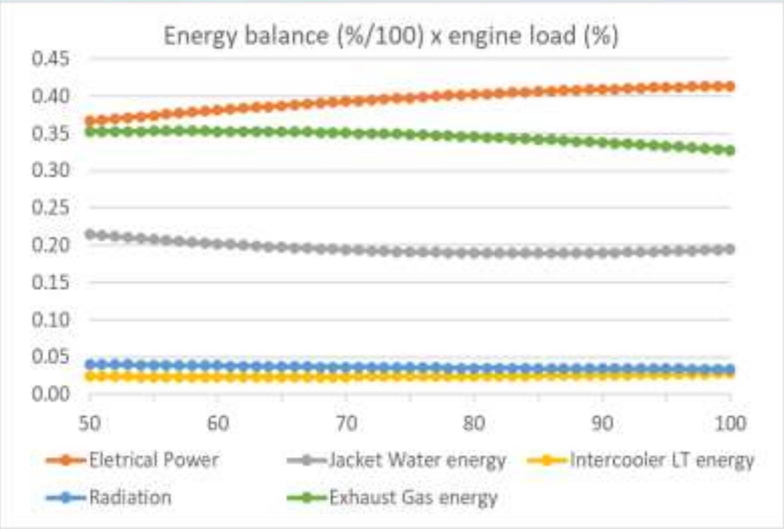

Figure 9 – engine part load energy balance

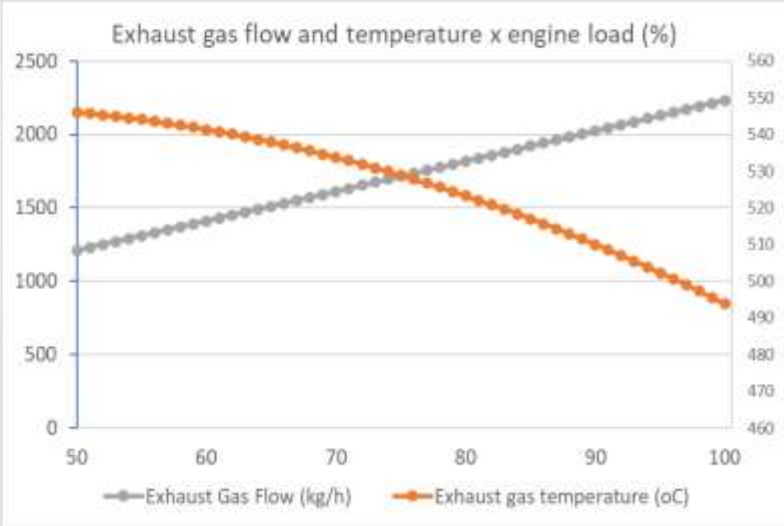

Figure 10 – engine part load exhaust gas flow (kg/h) and temperature (°C)

The engine utilized in this study is a Caterpillar CG 132-8 operating with natural gas (figures 9 and 10). The engine energy balance at full load reveals that the electric efficiency is 41.4% (400 kW), jacket water energy is 188 kW (19.46%), intercooler energy is 27 kW (2.79%), radiation energy is 33 kW (3.42%) and exhaust gas energy is 315.9 kW (32.7%). Engine part load energy balance is inserted in the software. Parasitic load is assumed as 3% - electricity used in pumps and fans.

The trigeneration system produces electricity, chilled water (flows 16 and 17), hot water for space heating (flows 14 and 15) and hot water for sanitary purposes (flows 12 and 13). Table 1 reveals the trigeneration system thermodynamic states.

Two main operating modes will occur: (i) cooling mode (hot summer days) and (ii) heating mode (cold winter days). At mild climate days the systems can operate combining the summer and winter modes. In the summer mode the absorption chiller uses most of the PC energy (flows 3 to 4) in the absorption chiller for chilled water production (flows 16 and 17), while in the winter mode the energy is used for space heating in HE1 (flows 14 and 15) – flow 3 by-pass the absorption chiller.

EGHE is designed and simulated using a Ganapathy book methodology [30] with an approach point of 16.6°C [flow 20 – flow 2]. HE1 and HE2 are designed and simulated using the NTU method. At HE2 1 kg/s of water enters at 10°C and is warmed to 40°C and at HE1 3.3 kg/s of water enters at 50°C and is warmed to 80°C (design condition).

The absorption chiller (AC) selection and simulation are based on manufacturer performance curves [31]. In the AC, chilled water is produced at 7.2 ◦C (5.5 ◦C temperature difference) with water entering the condenser at 29.4 ◦C. The performance data for the AC follows the ARI test procedure [32].

The engine exergy consumption rate is calculated for the fuel standard chemical exergy (51,737 kJ/kg), assuming a natural gas composition of 90% CH_4, 8% C_2H_6 and 2% C_3H_8 [33, 35]. For this composition fuel chemical exergy is equal to fuel lower heat value (45,462 kJ/kg) multiplied by 1.138. The ambient reference is set to T_0= 25◦C, and P_0= 100 kPa.

Figure 11 reveals the EUF (equation 1) and the exergy efficiency (equation 2), in summer mode while figure 12 reveals the EUF and the exergy efficiency operating in winter mode. The difference remains in the absorption chiller COP that is 0.8 and reduces the available energy in the trigeneration products (chilled water). The absorption chiller replaces electrical chillers assuming an electrical reduction factor of 0.8 kW/RT (COP equal to 4.4) [36-37].

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

$$\varepsilon = \frac{\dot{W}_{net} + \sum \dot{Ex}_{flows}}{\dot{m}_{fuel} . ech_{fuel}} = \frac{\dot{W}_{net} + \sum \dot{Ex}_{hot\,wat} + \sum \dot{Ex}_{chilled\,wat}}{\dot{m}_{fuel} . ech_{fuel}} \quad [2]$$

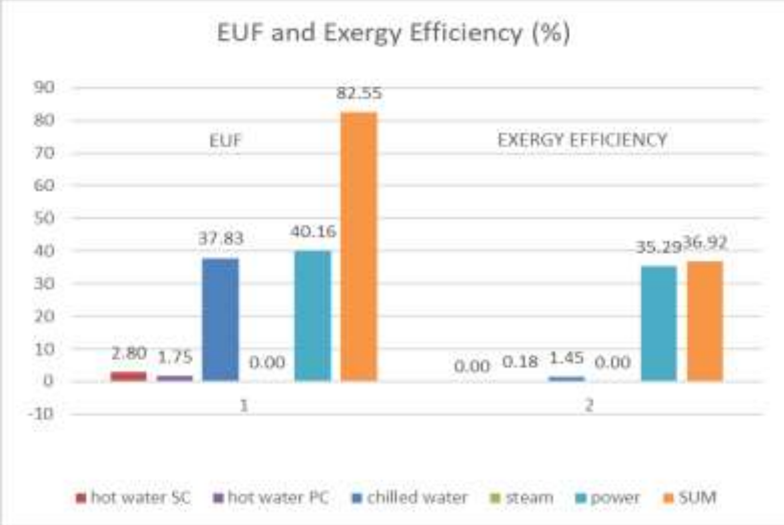

Figure 11 – EUF and exergy efficiency (cooling mode)

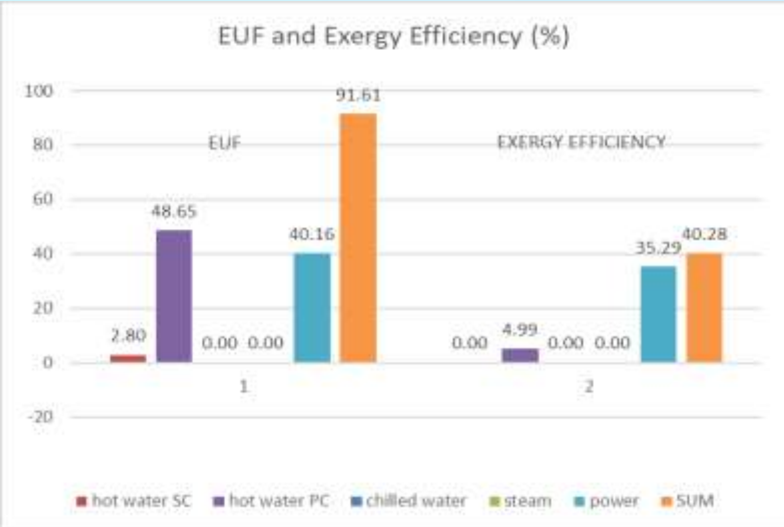

Figure 12 – EUF and exergy efficiency (heating mode)

Table 2 – Trigeneration products and primary energy consumption

	SUMMER MODE				WINTER MODE			
	ENERGY		EXERGY		ENERGY		EXERGY	
	(kW)	(%)	(kW)	(%)	(kW)	(%)	(kW)	(%)
hot water SC	27.08	2.80	-0.03	0.00	27.08	2.80	-0.03	0.00
hot water PC	16.95	1.75	1.98	0.18	470.03	48.65	54.89	4.99
chilled water	365.55	37.83	15.94	1.45	0.00	0.00	0.00	0.00
steam	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
power	388.00	40.16	388.00	35.29	388.00	40.16	388.00	35.29
SUM	797.58	82.55	405.89	36.92	885.12	91.61	442.86	40.28

Cogeneration / Trigeneration systems can also be evaluated utilizing the primary energy consumption (PEC) analysis. Figure 13 reveals a building/process energy consumption without (a) and with (b) a trigeneration system.

Equation 3 reveals the building/process energy consumption (low temperature hot water, medium temperature hot water, steam and electricity). Equation 4 reveals the PEC without a trigeneration system. The energy consumption is divided by the energy conversion efficiency.

$$\dot{E}c = \dot{E}_{hw1} + \dot{E}_{hw2} + \dot{E}_{st} + \dot{E}_{elet} \quad [3]$$

$$PEC_{without} = \frac{\dot{E}_{hw1}}{\eta_{hw1}} + \frac{\dot{E}_{hw2}}{\eta_{hw2}} + \frac{\dot{E}_{st}}{\eta_{st}} + \frac{\dot{E}_{elet}}{\eta_{elet}} \quad [4]$$

When comparing a building / process without and with a cogeneration / trigeneration system, the following equations can be used:

$$\dot{E}_{hw1s} = \dot{E}_{hw1} - \dot{E}_{hw1T} \quad [5]$$

$$\dot{E}_{hw2s} = \dot{E}_{hw2} - \dot{E}_{hw2T} \quad [6]$$

$$\dot{E}_{sts} = \dot{E}_{st} - \dot{E}_{stT} \quad [7]$$

$$\dot{E}_{elets} = \dot{E}_{elet} - \dot{E}_{eletav} - \dot{E}_{eletT} \quad [8]$$

$$\dot{E}_{eletav} = \dot{E}_{cwT}/COP \quad [9]$$

Trigeneration energy consumption can be calculated as:

$$\dot{E}_{trig} = \dot{E}_{hw1T} + \dot{E}_{hw2T} + \dot{E}_{stT} + \dot{E}_{cwT} + \dot{E}_{eletT} + \dot{E}_{losses} \quad [10]$$

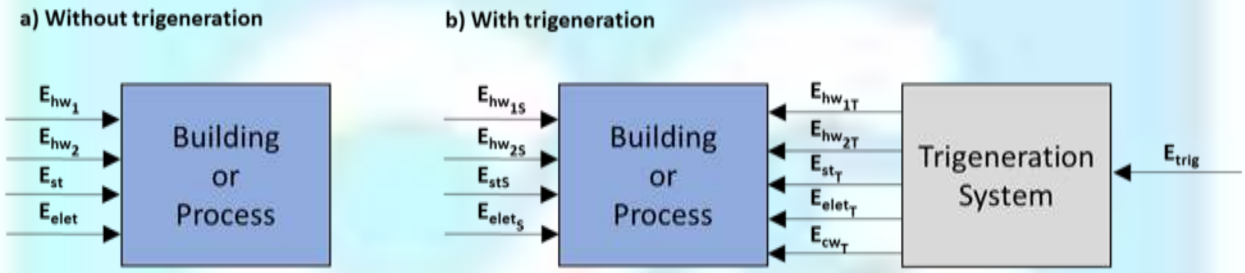

Figure 13 – building/process energy consumption

Trigeneration energy consumption is the prime mover energy consumption. The PEC of a cog/trigeneration system can be calculated using equation 11.

$$PEC_{withTrig} = \frac{\dot{E}_{hw1s}}{\eta_{hw1s}} + \frac{\dot{E}_{hw2s}}{\eta_{hw2s}} + \frac{\dot{E}_{sts}}{\eta_{sts}} + \frac{\dot{E}_{elets}}{\eta_{elets}} + \dot{E}_{trig} \quad [11]$$

If the PEC of a building/process with and without a cog / trig system are the same, equations 4 and 11 are equal:

$$PEC_{without} = PEC_{withTrig} \quad [12]$$

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

Defining hot water, steam and electricity production efficiency as the same with and without a cog/trig system:

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

Rearranging:

$$\eta_{elet} = \frac{\dot{E}_{elet}-\dot{E}_{elets}}{\dot{E}_{trig} - \left(\frac{\dot{E}_{hw1}-\dot{E}_{hw1s}}{\eta_{hw1}} + \frac{\dot{E}_{hw2}-\dot{E}_{hw2s}}{\eta_{hw2}} + \frac{\dot{E}_{st}-\dot{E}_{sts}}{\eta_{st}}\right)} = ETE \quad [15]$$

Equation 15 reveals the thermal efficiency at which the PEC with trigeneration is the same as without a trigeneration. It means that if a country thermal efficiency is lower than the calculated value, the trigeneration system will save primary energy and if it is higher it will rise the primary energy consumption. This value is defined as the Equivalent Thermal Efficiency (ETE).

Different hot water and steam efficiencies can also be assumed in equation 13, resulting in a different ETE equation (not shown here). Electricity, steam and hot water exports can also be evaluated with equation 15.

Taking into account the grid electricity loss:

$$\eta_{elet} = \frac{\frac{\dot{E}_{elet}-\dot{E}_{elets}}{F_{gridloss}}}{\dot{E}_{trig}-\left(\frac{\dot{E}_{hw}-\dot{E}_{hws}}{\eta_{hw}}+\frac{\dot{E}_{st}-\dot{E}_{sts}}{\eta_{st}}\right)} = ETE_{GL} \qquad [16]$$

As a basis of comparison, PES is also calculated using the 2012/27 EU directive [38] – (equation 17). Reference efficiencies are calculated according to harmonized efficiency reference values for separate production of electricity and heat discussed at the Delegated Regulation (EU) 2015/2402 of 12 October 2015 [39]. The voltage level is < 0,45 kV and an annual average temperature of 8.8ºC was calculated (figure 3). Thermal energy efficiency is 92% and thermal plant efficiency is 53% (no grid loss) and close to 47.7% (with grid loss and electricity export). The directive requires a 10% PES.

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

5. METHODOLOGY

The trigeneration system analysis and results developed in this study were obtained by means of the software (COGMCI) consisting of Fortran engineering programs and a Delphi interface [27]. Graphical results are generated by a spreadsheet (Excel) that imports data from result files. The Fortran programs are composed of one main algorithm and more than 30 subroutines dealing with (i) different engines, (ii) water and steam properties, (iii) exhaust gas properties, (iv) absorption chiller selection and simulation, (v) heat recovery steam generator (HRSG) design and simulation, (vi) HRSG economizer design and simulation, (vii) exhaust gas heat exchanger (EGHE) design and simulation, (viii) cooling tower design and simulation, (iv) air cooler design and simulation, among others.

The main program controls data entry, results and all calculations. Calculation procedures use polynomial curve fitting (engine and absorption chiller performance); deterministic modeling or mathematical representations of physical phenomena (heat transfer and pressure drops); and physical properties (water and exhaust gases). A computational algorithm involving several iterative procedures was developed, simulating the system as an integrated thermal system, i.e., considering all pieces of equipment as operating as a single system. It produces results as a function of demands, energy supplied by engine, design parameters, equipment performance and adopted assumptions. The hourly profile analysis simulation approximates the dynamic nature of energy consumption in buildings and the dynamics of thermal equipment performance in an integrated system by a series of quasi-steady-state operating conditions with one-hour time-steps, as used by Lebrun (1999) [40].

In this case study the computational algorithm is executed as an annual analysis simplified as 288 hours (twelve daily average groups of energy demands), as revealed in section 2. The analysis is used to predict the performance of a proposed engine trigeneration system producing electricity, hot water and chilled water (air conditioning).

Figure 14 reveals COGMCI available paths in order to find out a high efficiency engine cogeneration / trigeneration configuration. Engines real performance data can be defined, and a group of engines can be created. Engines (electricity production) operation mode can be defined as full load, electrical dispatch (following an electricity profile) or thermal dispatch (defining a minimal EUF). Engine exhaust gases can be used to produce steam at an HRSG, to warm engine PC water at an EGHE or can use it directly in a double effect exhaust gas and hot water absorption chiller. Engine PC energy (using or not the engine exhaust gas energy) can be used in a hot water absorption chiller, in an exhaust gas and hot water absorption chiller and/or in a hot water heat exchanger for space heating or process. Engine SC can be used for low temperature hot water production. Depending on the size (power) of the selected engine and the defined operational mode electricity can be imported and/or exported to the grid. Complementary steam, chilled water and hot water are calculated.

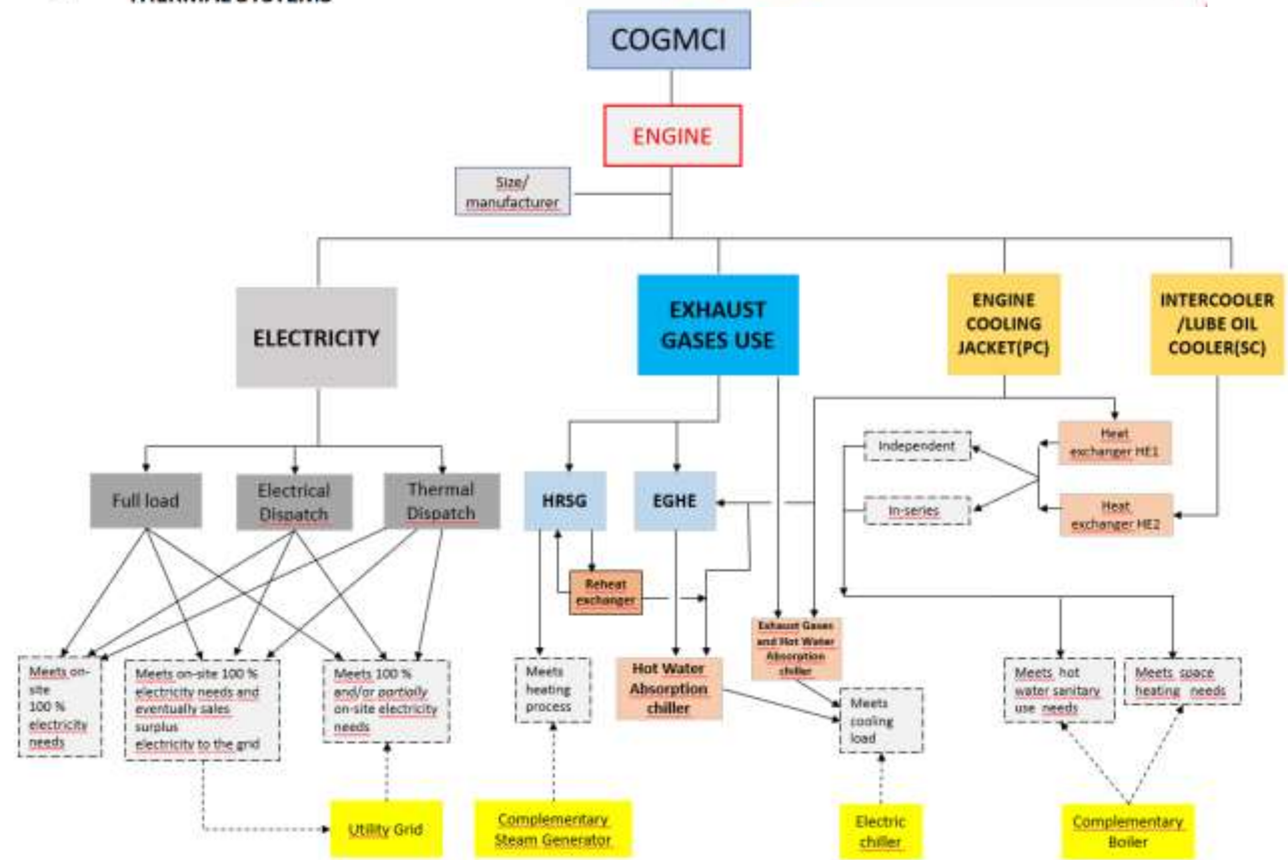

Figure 14 – COGMCI possibilities chart

6 CASE STUDIES

At this paper six different case studies are developed:

Case 1 – 400 kW engine operating at electrical dispatch.
Case 2 – 400 kW engine operating at full load.
Case 3 – 400 kW engine operating at thermal dispatch with a minimum 65% EUF.
Case 4 – 400 kW engine operating at thermal dispatch with a minimum 70% EUF
Case 5 – 400 kW engine operating at thermal dispatch with a minimum 75% EUF
Case 6 – 400 kW engine operating at thermal dispatch with a minimum 80% EUF

At electrical dispatch, electricity generated by the prime mover is controlled to satisfy the electric demand and the waste heat available drives all or part of the heat demand.

At full load the prime mover runs without any control and may cover or not the electric demand. The facility must be connected to the grid as surplus electricity is exported and complementary is imported.

At the thermal dispatch mode, the engine electricity production is controlled to reach a minimum EUF – the higher engine load that meets the defined EUF. At lower engine load some of the engine trigeneration products (electricity, space heating hot water, chilled water and/or sanitary use hot water) can be produced at a lower quantity or efficiency. If the defined EUF is not attended until an engine load equal to 50%, the analysis is assumed as converged and 50% engine load is defined as the operating hour condition.

For all operational modes, if waste heat is not enough to meet the thermal demand, supplementary components such as steam generators, boilers and electrical chillers are required to operate. In hours where the waste heat is not totally recovered, it must be discharged to the environment through rejection systems.

7 RESULTS

7.1 case 1 results

Figure 15 reveals the electricity demand and the engine total production in January and July. The electricity demand is corrected since the absorption chiller will attend a part of the cooling load, avoiding electric consumption in the electrical chiller. Between hours 1 to 5 and 22 to 23 in January and 0 to 4 and 23 in July the engine operates at its lower allowed load (50%) and electricity is exported to the grid. At the remaining hours the engine follows the electricity demand. The difference between the corrected electricity demand and the engine total production is the parasitic load (assumed as 3%).

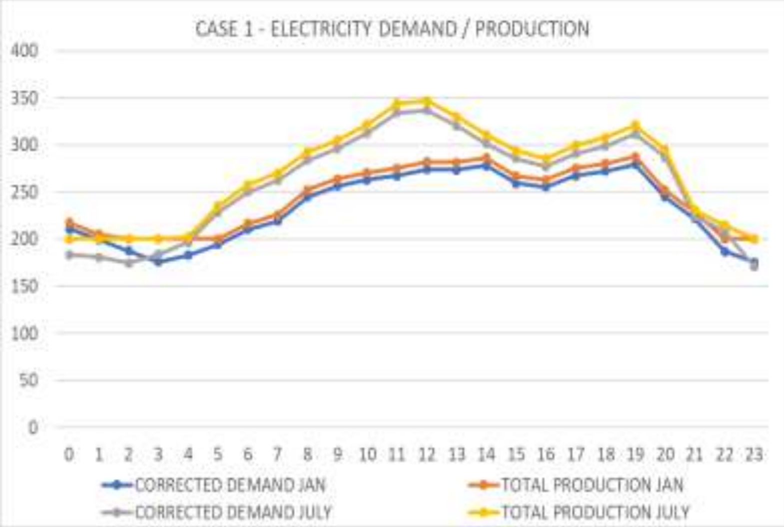

Figure 15 – case 1 electricity demand and production (kW) – January and July

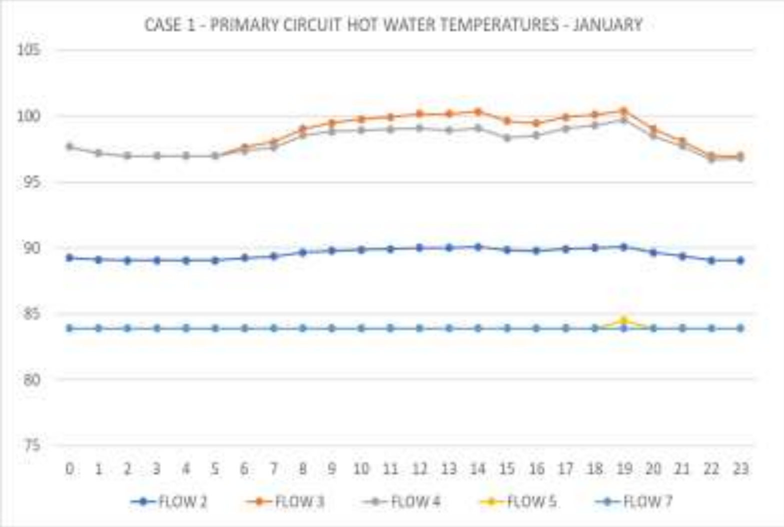

Figure 16 – case 1 primary circuit temperatures profiles – January

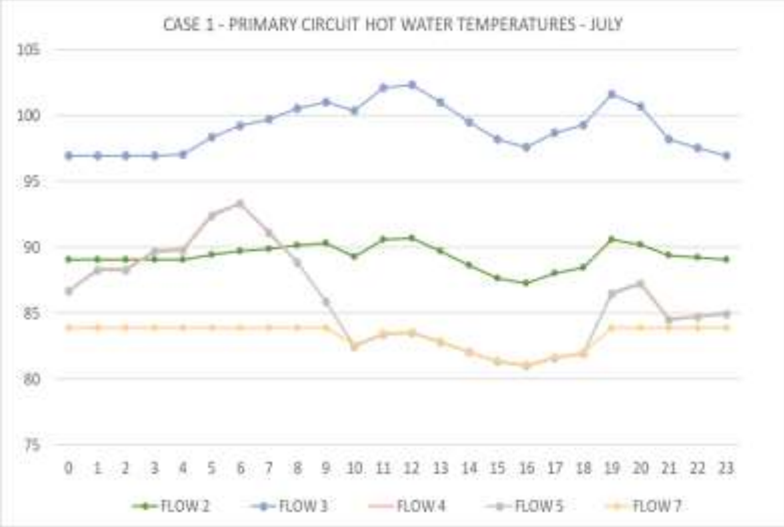

Figure 17 – Case 1 primary circuit temperatures profiles – July

Figure 16 shows the PC hot water temperature profiles in January. Water enters the engine at 83.89ºC [flow 7] and leaves the engine between 88 and 90ºC [flow 2] depending on the engine load. Water leaving the engine [flow 2] is warmed using the exhaust gas energy to between 97 and 100.5ºC [flow 3] depending on the engine load. Hot water enters the absorption chiller as flow 3 and leaves as flow 4, it can be seen that they are coincident at hours 0 to 5 and 23 since these hours have no cooling load (figure 6), at the remaining hours a small fraction of the PC energy is utilized at the absorption chiller, since flow 4 temperature is close to flow 3 temperature. Water enters HE1 as flow 4 and leaves as flow 5, almost all PC energy is being recovered (unless at hour 19) and complementary energy is necessary. At hour 19 an electricity demand/production peak (figure 15) and a reduction in space heating needs (figure 5) are verified.

Figure 17 reveals the PC hot water temperature profiles in July. Hot water enters the engine at 83.89ºC and leaves [flow 2] between 88 and 91ºC, depending on the engine load. Hot water leaves the EGHE between 97 and 102ºC [flow 3]. Flow 4 reveals the hot water temperature leaving the absorption chiller, it depends on both the engine load and the cooling load (figure 6). Flow 5 temperature is coincident with flow 4 since no heating load occurs in July. Between hours 10 and 19 the engine operates at part load and flow 3 temperature is different than in the design mode (table 2 – 104.6ºC) while the absorption chiller is operating at full load. The hot water absorption chiller recovers energy below design flow 7 temperature and a different than design condition is achieved at these hours, affecting all PC temperatures [flows 2 to 7].

Figure 18 reveals the engine cog/trig system EUF. Higher EUF (90-91%) occurs in winter months mainly due to the space heating loads (figure 5). June, July and August revealed a EUF as high as 81% at the peak cooling load hours. November and March were the best mild months results, while at the other months EUF is between 50% and 75%. An average EUF equal to 73.6% was calculated.

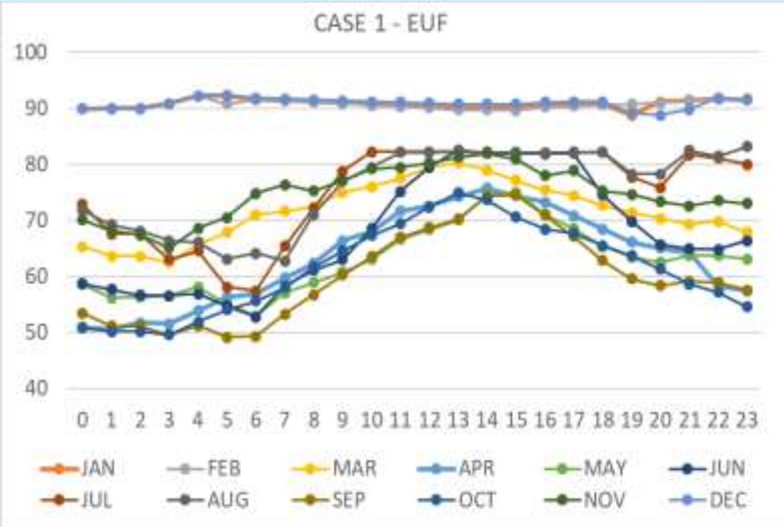

Figure 18 – case 1 EUF

Figure 19 reveals the engine load. Summer months have a higher engine load due to a higher demand (space cooling). Engine load is higher at mild climates months than in winter months (note that at figure 16 flow 3 temperature is lower than in figure 17). An average engine load equal to 62.5% was calculated.

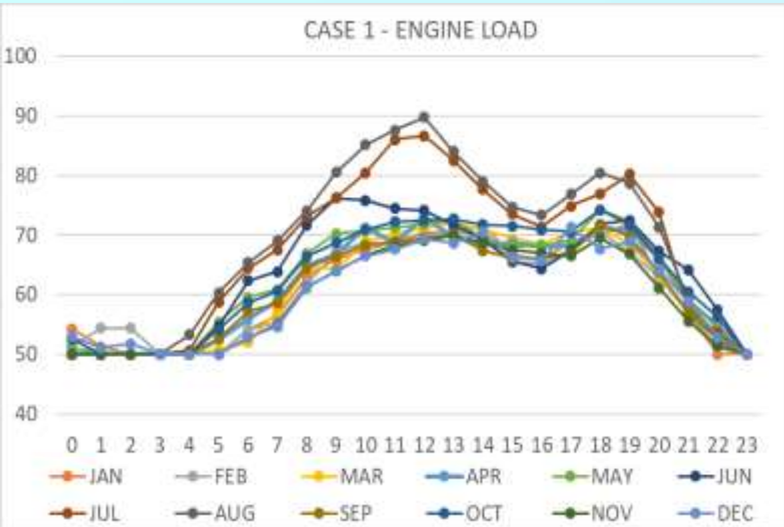

Figure 19 – case 1 engine load

Secondary circuit energy is recovered at HE2 to warm sanitary use hot water. Sanitary use hot water demand can be as high as 165 kW (figure 7). Secondary circuit energy is 27.08 kW with the engine at full load (table 2). Complementary energy is necessary and should be supplied by the existing fueled boilers.

7.2 case 6 results

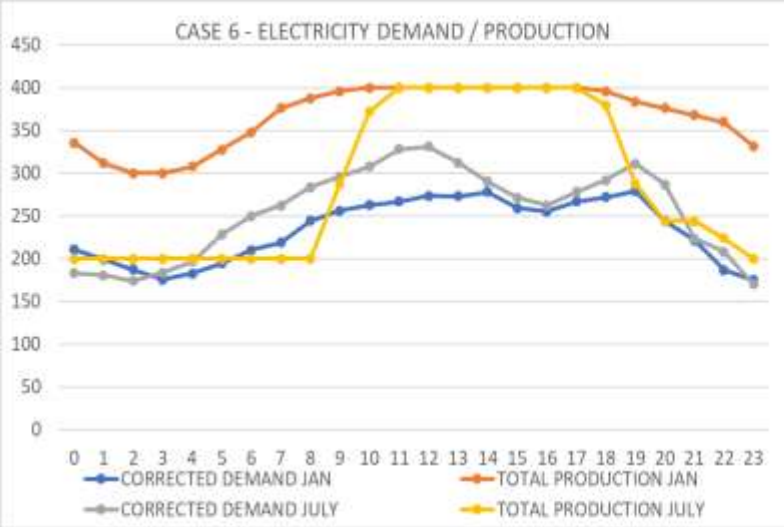

Figure 20 – case 6 electricity demand and production – January and July

Figure 20 reveals the electricity demand and the engine total production in January and July. The electricity demand is corrected (absorption chiller avoids electrical chiller use). In January the engine operates producing electricity between 300 and 400 kW. The engine maintains a high load since the EUF is higher or equal to 80% (figure 23). In July the engine operates at 50% engine load between hours 0 to 8 and 23, since a EUF higher or equal to 80% is not reached (low cooling load). Between hours 9 to 22 a higher engine load is verified since the calculated EUF is higher or equal to 80% (high cooling load). Between hours 11 to 17 the engine operates at full load. The parasitic load is 3%.

Figure 21 shows the PC hot water temperature profile in January. Water enters the engine at 83.89ºC [flow 7] and leaves the engine between 90 and 92.2ºC [flow 2] depending on the engine load. Water leaving the engine [flow 2] is warmed using the exhaust gas energy to between 100.8 and 104.6ºC [flow 3] depending on the engine load. Hot water enters the absorption chiller as flow 3 and leaves as flow 4. Water enters HE1 as flow 4 and leaves as flow 5. The difference between flow 5 and flow 7 temperature is related to the rejected PC energy.

Figure 22 reveals the PC temperature profiles in July. Hot water enters the engine at 83.89ºC and leaves [flow 2] between 89.1 and 92.2ºC, depending on the engine load. Hot water leaves the EGHE between 97 and 104.6ºC [flow 3]. Flow 4 reveals the hot water temperature leaving the absorption chiller, it depends on both the engine load and the cooling load (figure 6). Flow 5 temperature is coincident with flow 4 since no heating load occurs in July.

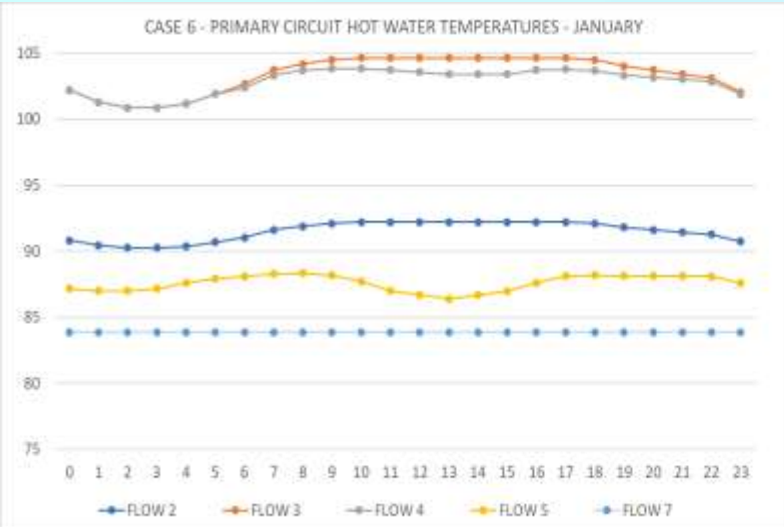

Figure 21 – case 6 primary circuit temperature profiles – January

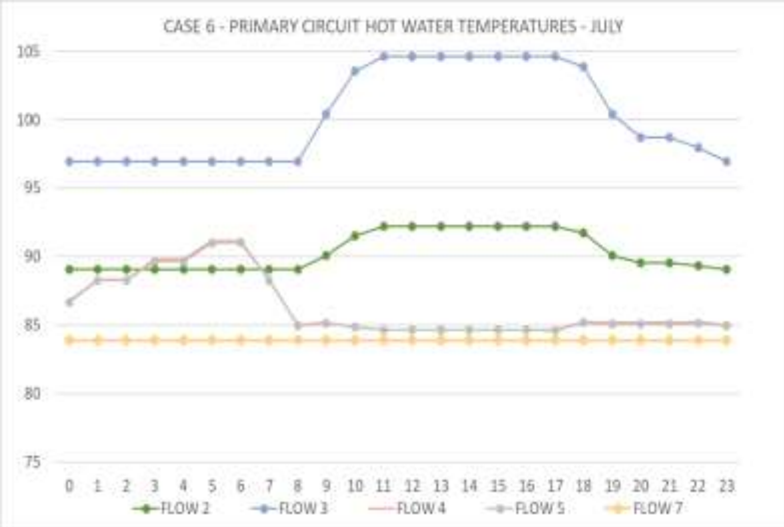

Figure 22 – case 6 primary circuit temperature profiles – July

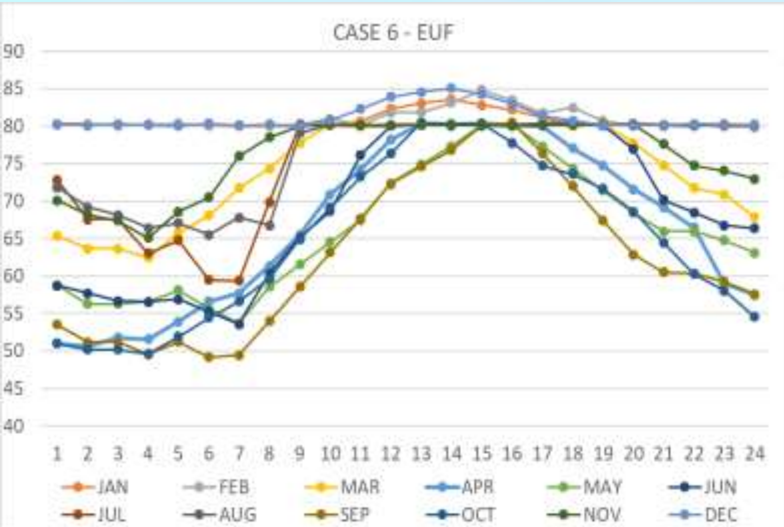

Figure 23 – case 6 EUF

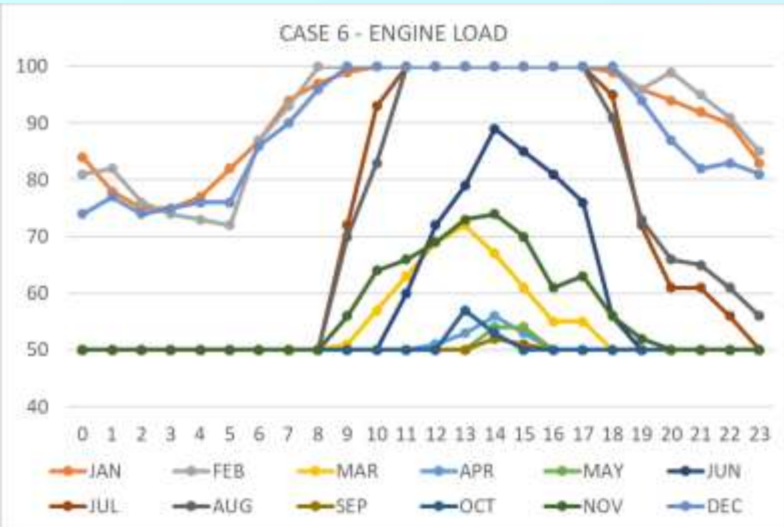

Figure 24 – case 6 engine load

Figure 23 reveals the engine cog/trig system EUF. Higher EUF (90-91%) occurs in winter months mainly due to the space heating loads (figure 5). Summer months revealed a EUF as high as 81% at the peak cooling load hours. November and March were the best mild months results. An average EUF equal to 72.7% was calculated.

Figure 24 reveals the engine load. Winter months have a higher engine load, since the space heating demand is high and an 80% EUF is reached with high engine loads. July and August have engine loads between 50% (hours 0 to 8) and 100% (hours 11 to 17) depending mostly on the cooling load. June revealed engine loads between 50% and 90% (hour 15) – cooling load is lower in June (see figure 6). Mild climates months operates most of the time at 50% engine load except at the hours a high cooling load and/or space hating load is verified. An average engine load equal to 65.4% was verified.

The SC results are similar to case 1.

Table 3 – cases 1 to 6 data summary

		Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
		400 kW ED	400 kW FL	400 kW EUF 65%	400 kW EUF 70%	400 kW EUF 75%	400 kW EUF 80%
1	Total electricity consumption (kW.h/yr)	2,287,420	2,287,420	2,287,420	2,287,420	2,287,420	2,287,420
2	Total corrected electricity consumption (kW.h/yr)	2,099,842	2,094,549	2,094,549	2,094,549	2,094,549	2,094,549
3	Net electricity production (kW.h/year)	2,124,836	3,398,880	2,775,632	2,572,832	2,390,418	2,221,750
4	electricity to (-)/ from (+) grid (kW.h/year)	-24,994	-1,304,331	-681,083	-478,283	-295,869	-127,201
5	Hot water for space heating consumption PC (kW.h/yr)	1,199,016	1,199,016	1,199,016	1,199,016	1,199,016	1,199,016
6	Hot water for space heating production PC (kW.h/yr)	1,149,477	1,199,016	1,199,016	1,199,016	1,199,016	1,199,016
7	Hot water for space heating complementary PC (kW.h/yr)	49,539	0	0	0	0	0
8	Hot water for sanitary use consumption SC (kW.h/yr)	339,424	339,424	339,424	339,424	339,424	339,424
9	Hot water for sanitary use production SC (kW.h/yr)	117,256	160,330	145,254	135,905	127,536	121,131
10	Hot water for sanitary use complementary SC (kW.h/yr)	222,168	179,094	194,170	203,519	211,888	218,293
11	natural gas consumption engine (kW.h/yr)	5,691,553	8,469,389	7,113,011	6,671,639	6,274,981	5,908,410
12	Cooling load (RT/yr)	251,500	251,500	251,500	251,500	251,500	251,500
13	abs chiller production (RT/yr)	233,899	240,487	240,487	240,487	240,487	240,487
14	EUF (%) - energy utilization factor	73.6%	66.2%	68.3%	69.6%	71.0%	72.7%
15	engine load factor (%)	62.5%	100.0%	81.7%	75.7%	70.0%	65.4%
16	Exergy efficiency	36.2%	37.8%	36.6%	36.3%	36.0%	35.8%
17	Thermal energy recovered (%) - average	36.64%	25.99%	30.73%	32.63%	34.55%	36.59%
18	Engine electric efficiency (%) - average	37.3%	40.1%	39.0%	38.6%	38.1%	37.6%
19	PES -Annex II Energy Efficiency Directive (Directive 2012/27/EU)	15.2%	10.5%	13.0%	13.9%	14.7%	15.6%
20	Equivalent Thermal Efficiency (%) - no grid loss	54.0%	51.6%	52.8%	53.3%	53.8%	54.4%
21	Equivalent Thermal Efficiency (%) - 10% grid loss	60.0%	57.3%	58.7%	59.2%	59.8%	60.4%

7.3 General results

Table 3 reveals a summary of all case studies. At line 1 the annual electricity consumption is revealed as 2,287,420 kWh/year. Line 2 reveals the corrected electricity consumption (absorption chiller avoiding electrical chiller use). Case 1 has the higher consumption and cases 2 to 6 have the same consumption revealing that at full load and hermal dispatch mode (independent of the defined EUF) all cases produced the same chilled water amount at the absorption chiller (lines 12 and 13). Line 3 reveals the net electricity production, case 1 produced less electricity than the others with the highest EUF. At thermal dispatch as high is the EUF, lower is the electricity production since the engine load is reduced trying to reach the defined EUF. Line 15 reveals the average engine load.

Line 4 reveals the electricity import and export. Cases 1 to 6 export electricity to the grid. At the electrical dispatch mode less electricity is exported.

Line 5 reveals the space heating hot water consumption. Case 1 produced close to 96% of the necessary energy (figure 16) while cases 2 to 6 produced 100% (line 6).

Line 8 reveals the sanitary use hot water consumption. No cases met the consumption, better results depend on the engine load. As high is the engine load more energy is recovered at HE2. A solar thermal system can be used as a complementary system, reducing fossil fuel use and rising the PES – not evaluated at this study.

Line 11 reveals the engine natural gas consumption. Engine fuel consumption is affected by the produced power and engine load (electrical efficiency).

Line 14 reveals the EUF. The higher value occurred for case 1, mainly due to a high EUF in winter months with reduced engine load (figure 26). At the remaining months case 6 has a higher EUF (figure 25).

Line 16 reveals the exergy efficiency. Case 2 revealed the higher exergy efficiency (37.75%), since the engine operates at full load (higher electrical efficiency). Exergy efficiency results have a big influence of the produced power and are mainly influenced by the engine load (electrical efficiency), since relatively small differences at the thermal products are verified (lines 6, 9 and 13). Case 2 has a higher exergy efficiency than cases 5 and 6, despite a lower average engine load. This can be justified due to (i) a higher exergy efficiency in the spring and autumn months (figure not shown) – higher engine load (figure 26) and (ii) a bigger reduction on the electrical efficiency as loads are lower.

Line 17 reveals the thermal energy recovered. Case 1 has the higher average value mainly due to the winter months results and a lower average engine load. Case 6 is the second better result since less electricity is produced (compared to cases 2 to 5) and almost the same energy is recovered (lines 6, 9 and 13).

Line 18 reveals the average electrical efficiency. Higher engine load has higher electrical efficiency.

Line 19 reveals the PES calculated using the EU directive 2012/27. All cases reached the necessary 10% PES to comply with the directive.

Line 20 reveals the ETE with no grid loss (equation 15). ETE between 51.6% and 54.4% were calculated. The lower ETE occurs for case 2 (also has the lower EUF). The higher ETE occurs in case 6 (54.4%), being followed by case 1 (54%).

Line 21 reveals the ETE with a 10% grid loss (equation 16). ETE between 57.3% (case 2) and 60.4% (case 6) were calculated.

Figure 25 reveals the average monthly EUF. Higher EUF occurs in winter (due to space heating loads) and summer (due to cooling loads). Case 1 has the higher EUF in winter months while case 6 has the highest EUF in the remaining months.

Wang et al [41] evaluated an engine CCHP system, an energy efficiency between 57.9 and 89.5% was calculated. Calise et al [42] evaluated three different strategies of an engine trigeneration system for an Italian hospital, global efficiencies between 75.6% and 90.3% were calculated. Wang et al [07] evaluated an engine trigeneration system with different fuels, efficiencies between 55 and 85% were revealed, depending on the fuel and the engine load. Wang et al [08] evaluated the use of hydrogen in an engine trigeneration system using the Eclipse software, efficiencies between 55 and 85% were predicted.

Figure 26 reveals the engine load factor. Case 1 has a lower value in the winter with rising engine loads in spring and autumn, the higher engine loads occurs in summer due to air conditioning use. Case 2 has a fixed engine load of 100% (engine full load). Cases 3 to 6 have a similar behavior, higher loads in winter (due to high space heating loads) and summer (due to high cooling loads) and reduced loads in spring and autumn. Case 6 has a lower average engine load among the thermal dispatch mode cases.

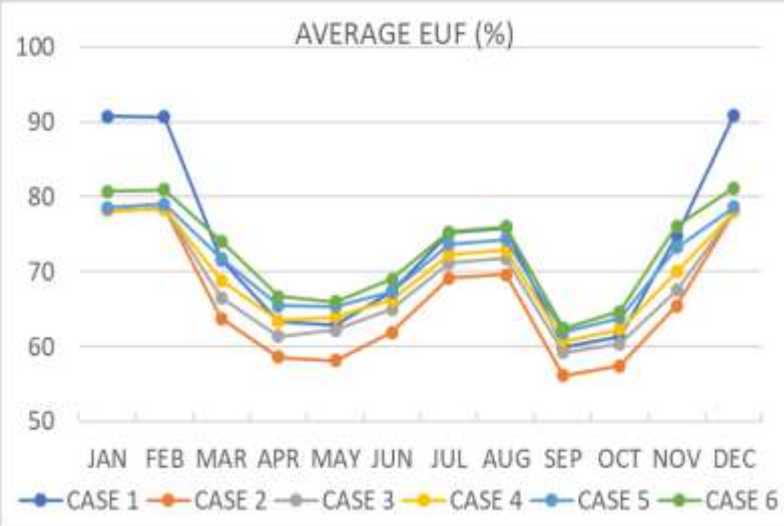

Figure 25 – cases 1 to 6 average EUF

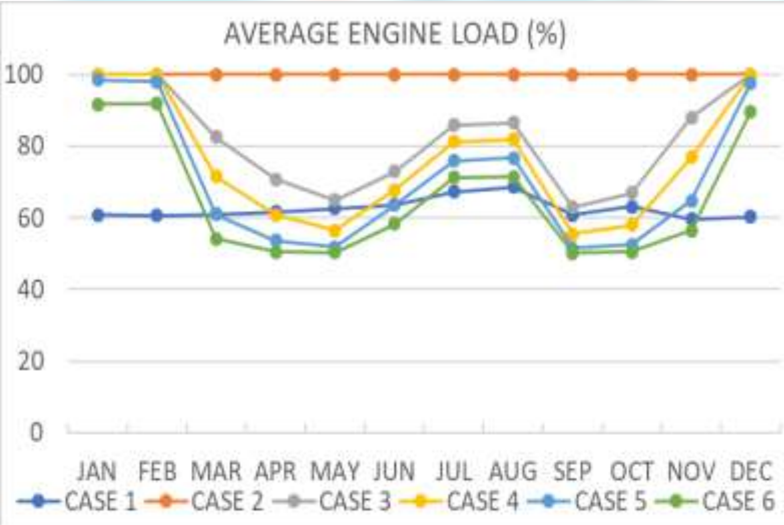

Figure 26 – cases 1 to 6 average engine load

Table 4 – Engine load data

Engine load	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
at 50% load	1887	0	2057	3092	3889	4561
above 50 to 60 % load	1793	0	670	491	488	641
above 60 to 70 % load	2879	0	365	428	733	486
above 70 to 80 % load	1866	0	429	397	336	695
above 80 to 90 % load	335	0	368	551	602	573
higher than 90%	0	8760	4871	3801	2712	1804
	8760	8760	8760	8760	8760	8760

Table 4 reveals the number of hours the engine operates between 50 and 100% for each evaluated case. Case 1 has most of the hours between 60 to 80% and 21.5% of the hours at 50% (lower admissible engine load). Case 2 operates 100% of the time at 100% engine load. Cases 3 to 6 results reveal that as stringent is the EUF lower is the engine load, case 6 operates 52% of the hours at 50% engine load.

8 CONCLUSIONS

This paper aims to contribute to the engine cog/trigeneration systems research, exploring (i) a new efficiency indicator (ETE) used to compare centralized thermal plants and site heat production with decentralized engine cog/trig system, (ii) oversized prime movers (engine) able to export electricity to the grid and (iii) a new thermal dispatch mode (multiple products) for engines that can be used in real systems to assure a high efficiency operation.

The EnergyPlus software [28] was used to simulate the building and predict the annual energy consumption. The COGMCI software was used to develop the cog/trig analysis. All the engine cog/trig system results were revealed by the COGMCI software, although only some figures were revealed in this paper.

Oversized engines can benefit from a higher electrical efficiency than smaller ones, can operate at a demand response strategy and can play an important role in the transition from fossil fuels to renewables as they are flexible in the operating mode being able to operate at thermal dispatch, electrical dispatch or full load.

ETE should be compared with countries average thermal efficiency. All operation modes evaluated in this study revealed a better ETE than countries average thermal efficiencies, even when neglecting the grid loss. ETE results are in agreement with the European directive results [38].

Graus [43] revealed some countries average weighted thermal efficiency as 38% for coal, 45% for natural gas and 38% for oil (neglecting grid losses). Marasso et al [44] revealed that at a TERNA report the average thermal efficiency in Italy was 44.7% (including grid losses) in 2017. The World Energy Council [45] estimates the average loss at world electrical grids as 12% and the average thermal efficiency as 41% for natural gas and 34% for coal (neglecting grid loss).

Thermal dispatch mode and oversized engine cog/trig systems is always looking for a high efficiency operation being able to export electricity to the grid at grid peak hours and/or low intermittent renewables production hours, just changing the operation mode. Lower engine loads have a higher potential for electricity exports.

Thermal dispatch mode can be used to reach incentive programs or legislations. The challenge is to develop an algorithm able to control the engine output looking for a high efficiency operation.

The best strategy depends on the match of the energy loads, electrical dispatch had a great result but the thermal dispatch with a high EUF revealed to be the best solution when comparing the ETE and the PES using the European directive.

The performance of the trigeneration system evaluated here (figure 8) with a 300 kW power output engine with the same energy balance used in this study (figure 9), operating at electrical dispatch was also investigated (results not shown). It revealed a high average engine load, EUF, PES and ETE than cases 1 to 6, but with a reduced power to export to the grid.

At high EUF thermal dispatch mode the ETE can be higher even with decreasing engine thermal efficiency (engine load) and lower PC e SC energy recovery temperatures, due to a better match between the cog/trig products and the energy demands. A detailed analysis of engine part load operation, energy demand and energy recovery need to be developed.

Engines are in constant development, the data used here was obtained in 2013, we can expect a better performance on this engine.

Utilities and/or producers are being remunerated to maintain backup and peak loads thermal plants. These values are already included in our electrical bills. Governments should create rules to use this resource to incentive high efficiency solutions able to contribute to reduced emissions and grid stability.

Resilient and reliable electricity production will face an important role in the transition from fossil fuels to renewables, countries should try to raise their average thermal efficiency including even the thermal plants that just operate in the peak load hours. Oversized engines cog/trig systems can be connected to a smart grid and operate at full loads at these hours exporting electricity to the grid with a high ETE and PES.

High efficiency solutions trend to use existing infrastructure (grid and natural gas network) even considering higher future demands.

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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)
ech_{fuel}	fuel chemical exergy (kW)
Ex	exergy flow (kW)
To	reference temperature (K)
U	Global Heat Transfer Coefficient (W/m^2.K)
ε	exergy efficiency
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
HRSG	heat recovery steam generator
EGHE	exhaust gas heat exchanger
HE	heat exchanger
CCHP	combined cooling and heating power
ORC	organic rankine cycle
TES	thermal energy storage