# Experimental assessment of a small-scale trigeneration plant with a natural gas microturbine and a liquid desiccant system

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**Abstract**

Trigeneration allows the thermal energy recovered from the prime mover of a cogeneration plant to be exploited to produce a cooling effect. In this way, when tertiary applications are considered, it is possible to extend the working hours of the plant over the heating period, and to provide summer air conditioning through thermally activated technologies. The paper has the aim of showing the experimental results of a real CHCP system operating at full load and partial load. The data are presented for both cogeneration and the trigeneration configurations. The test plant is installed at the Politecnico di Torino (Turin, Italy), and is composed of a natural gas 100 $kW_{el}$ microturbine coupled to a liquid desiccant system.
A preliminary energetic and economic performance, at full load operation, is assessed and compared with a partial load operation strategy. The primary energy savings are calculated through a widely accepted methodology, proposed by the European Union. The economic proficiency of the installation is also investigated, and the results are commented on and discussed.

**Keywords**

Combined Heat Cooling and Power (CHCP), trigeneration, liquid desiccant, micro gas turbine, experimental data, partial load, economic assessment.

## Introduction

The way primary energy consumption is reduced and energy applications efficiency is increased today represents an important research topic.
Among the actual technologies that allow an efficient exploitation of primary energy, the possibility of producing thermal and electrical energy from the same process (Combined Heat and Power production, CHP) is one of the most interesting opportunities of reducing energy consumption in both residential and industrial applications. Moreover, the conversion of thermal energy into cooling energy, by means of thermally activated technologies (TAT), extends the cogeneration concept to trigeneration (Combined Heat, Cooling and Power production, CHCP) and allows a CHP plant to operate in the summer season, by providing, for example, air conditioning in tertiary applications.

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Intense investigations on the performances of CHCP plants have been carried out over the last few years to evaluate the energetic and economic convenience of this technology.
Many authors ([1], [2]) have conducted detailed studies on the analytic method which should be used to study small scale trigeneration plants, in terms of energetic indexes and operation strategies. Other researches have dealt with the development of simulation models ([3], [4]), that are able to reproduce the behaviour of a CHCP plant, for different load requirements and ambient conditions.
Economic and energetic aspects have also been studied in great detail, e.g. comparisons between different CHCP plants based on the energy saving performance or their operation profitability. Some studies on this subject are reported in [5] and [6], where the authors based their analysis on manufacturers' data and for full load operation strategies.
It is important to underline that discrepancies between manufacturers' data and on-field test data may occur. Thus, real operational data can differ from the datasheet performances, and the results obtained from energetic and economic assessments can be less representative than the operational figures obtained from the real plants.
In the literature it is rather difficult to find experimental data on CHCP plant operation, and the availability of performance characteristics at off-design conditions is limited; nevertheless, sets of experimental data of a microturbine (MGT) coupled to an absorption chiller are shown in references [7] and [8], and an energetic assessment of the operational performances is carried out. Furthermore, in [9] the operational data at different conditions are shown for a reciprocating engine coupled to a liquid desiccant cooling system.

The present paper is aimed at presenting a set of experimental data, related to cogeneration and trigeneration configurations, of a small-scale CHCP plant installed at the Politecnico di Torino (Turin, Italy), which is constituted by a 100 $kW_{el}$ natural gas microturbine coupled to a liquid desiccant system. The plant is part of the "Ecoener.lab" laboratory, a CHCP and renewable energy systems laboratory which has the aim of exploiting different kinds of installations for scientific and technical research purposes.
The obtained data have been used to carry out a preliminary energetic and economic comparison between full load and partial load operations of the plant.

## Plant and measurement system description

A small-scale trigeneration plant has been set up and installed at the Politecnico di Torino, Turin, Italy. The plant was conceived to provide an air – conditioning service to a small building where several teaching classrooms are located. The system is also used for didactics and scientific research.
The main components of the plant are a natural gas microturbine and a desiccant cooling system. The main technical data of these components are shown in Table 1 and Table 2.
The electrical, heating and cooling capacities of the plant are 100/170/80 kW, respectively. The heat is recovered from an exhaust gas/water heat exchanger. The cogenerator has an electronic power unit, made up of an AC/DC-DC/AC converter, which allows the MGT to operate at a nominal fixed speed of 68000 rpm, while delivering 50 Hz AC to the grid, even at partial load conditions.
The heat recovered from the prime mover is exploited in the desiccant cooling unit, a Thermally Activated Technology (TAT) device. Each unit is composed of two sections: a conditioner and a regenerator. The conditioner is able to produce a cooling effect from the dehumidification obtained through the sorption of the humidity in an external airflow of 5000 $m^3/h$, by means of an LiCl-water solution. Then, the moisture is desorbed from the solution in the regenerator, by means of a second external 5000 $m^3/h$ air flow [5]. The treated air is then sent to the Air Handling Unit of the building.
The experimental data shown in this paper have been obtained with three desiccant units in operation.
The plant configuration, in cogeneration and trigeneration mode, are shown in Figure 1 and Figure 2.

**Table 1: Main manufacturer's data of MGT**

| | |
|---|---|
| Manufacturer and model | Elliott Energy Systems - TA100R |
| Fuel | Natural gas |
| Nominal fuel power | 345 kW |
| Gross electrical power | 105 $kW_{el}$ |
| Net electrical power | 100 $kW_{el}$ |
| Speed | 68000 rpm |
| Power electronic | AC/DC - DC/AC converter |
| Recovered thermal power | 170 $kW_{th}$ |
| Fuel gas pressure delivered by the grid | 0.02 bar |
| Fuel gas pressure delivered to the combustion chamber | ~ 5 bar |

**Table 2: Main manufacturer's data of each desiccant cooling unit**

| | |
|---|---|
| Manufacturer and model | DuCool-Du Handling |
| Process air mass flow | 5000 m3/h |
| Regeneration air mass flow | 5000 m3/h |
| Dehumidification nominal capacity | ~ 42 kW |
| Dehumidification capacity | ~ 50 – 60 l/h |
| Desiccant solution | LiCl - water |
| Number of operating units | 3 |

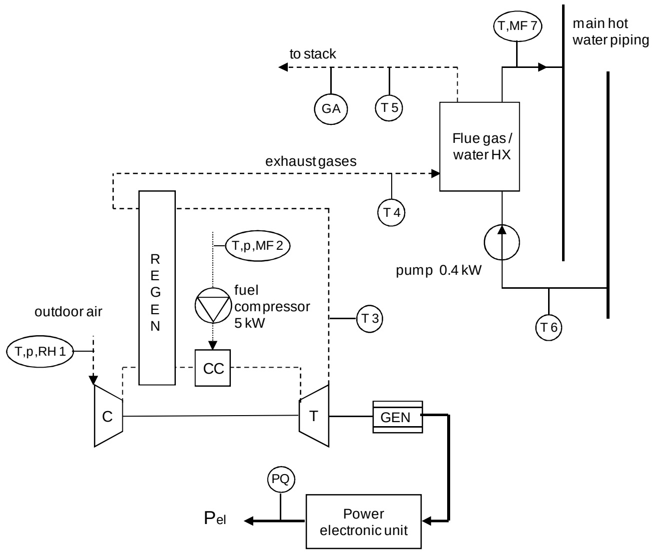


**Figure 1: Cogeneration mode. Plant scheme with sensors and auxiliary component power**

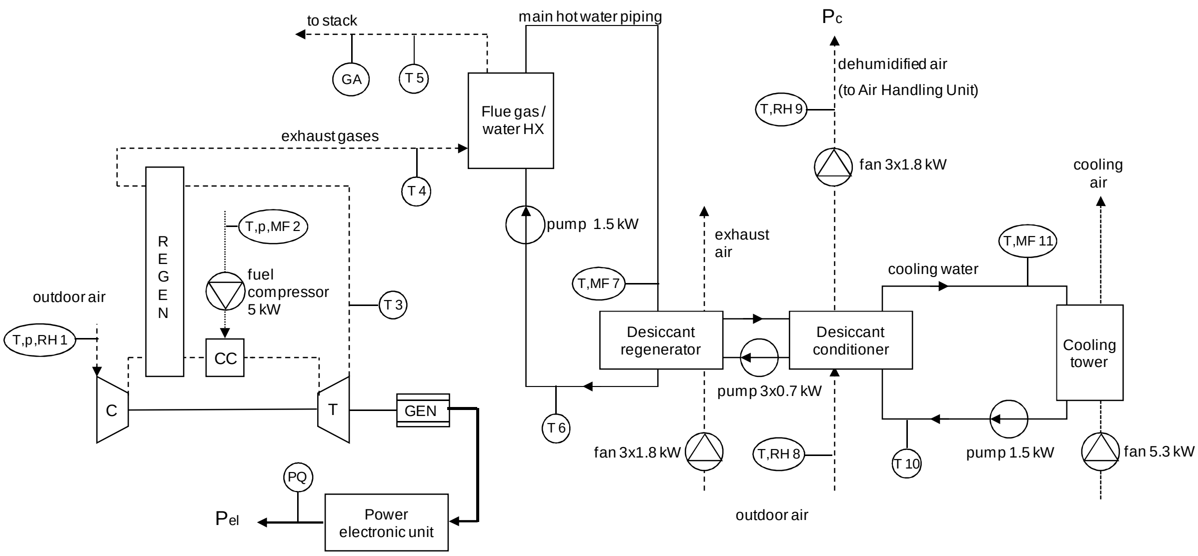


**Figure 2: Trigeneration mode. Plant scheme with sensors and auxiliary component power**

The experimental data are acquired by a measurement system (see Figure 1 and Figure 2) and recorded by a Labview monitoring tool. A set of temperature, pressure and mass flow meters has been set up and integrated in the existing plant configuration at the Politecnico di Torino. A description of the measurement instruments is given in Table 3.

**Table 3: Plant measurement system**

| Code | Instrument | Accuracy |
|---|---|---|
| T1 | Resistance temperature detector class A | ±0.2°C |
| T8, T9 | Resistance temperature detector class A | ±0.15°C @ 0°C<br>±0.35°C @ 100°C |
| T3, T4, T5 | Thermocouple type K | ±1°C |
| T2, T6, T7 | Thermocouple type K | ±0.5°C |
| T10, T11 | Resistance temperature detector class A | ±0.15°C @ 0°C<br>±0.35°C @ 100°C |
| p1 | Piezoresistive barometer | ±0.4 mbar @ 20°C |
| p2 | Piezoresistive pressure sensor | ±0,075% (deviation) |
| PQ | Grid analyzer | Voltage and current ±0.25% FS<br>Power ±0.50% FS<br>Power factor ±1% FS<br>Harmonic distortion ±0.20% FS |
| RH1 | Ta-Cr capacitive sensor | ±2% |
| RH8, RH9 | Ta-Cr capacitive sensor | ±3% |
| MF2 | Diaphragm gas meter | ±0,5% |
| MF7, MF11 | Electromagnetic flow sensor | 0,2% |
| GA | Gas analyzer | O2 ±0.3 Vol.%<br>CO ± 20<br>NO/No2 ±5 ppm |

## Experimental data

A set of experimental data is presented in this section. The set refers to two operational tests that were carried out, in cogeneration mode, on a typical winter's day, and in trigeneration mode, on a typical summer's day. Table 4 shows the ambient conditions for the two days. In each experimental test, the system is operated at four different loads: full load and 80%, 60%, 40% of the full load.

**Table 4: Ambient conditions during tests**

| | Cogeneration mode | Trigeneration mode |
|---|---|---|
| Date | 02 Feb 2011 | 13 Sep 2010 |
| p1 - average ambient pressure (bar) | 0.993 | 0.980 |
| T1 - average ambient temperature (°C) | 2.5 | 25 |
| RH1 - average ambient relative humidity (%) | 80 | 45 |

### Cogeneration mode

The main experimental data of the cogeneration test (listed in Table 5) represent a typical operating day in the winter period. The main temperature trends are shown in Figure 3.

The gross electrical power $P_{el,g}$, delivered from the MGT generator, is measured by a grid analyzer; the total energy $P_{el,t}$, produced by the microturbine (taking into account the auxiliaries consumption of the prime mover), is calculated as the difference between $P_{el,g}$ and the power of the on-board fuel compressor (5 kW). The net thermal power $P_{th,n}$ is determined, from experimental data, using the following equation:

$$P_{th,n} = \dot{m}_{MF7} \bar{c}_{p,H_2O} \cdot (T_6 - T_7)$$

where $\dot{m}_{MF7}$ and $\bar{c}_{p,H_2O}$ are the mass flow rate and the average specific heat at constant pressure of water, respectively; $T_6$ and $T_7$ are the inlet and outlet temperatures of the water in the heat exchanger.
The fuel input power $P_{fuel}$ is determined as follows:

$$P_{fuel} = H_{i,f} \cdot \dot{m}_{MF2} \cdot \frac{p_2 \cdot T_0}{p_0 \cdot T_2} \cdot \rho_0$$

where $\dot{m}_{MF2}$ is the volumetric mass flow rate for the test conditions; T, p and ρ are the temperature, pressure and density of the fuel for the test conditions (subscript 2) and for the Standard Conditions ($T_0$=15°C, $p_0$=1.013 bar, subscript 0); $H_{i,f}$ is the low heating value of the fuel, which is assumed as 9.45 kWh/Sm$^3$.

**Table 5: Test in cogeneration mode. Main experimental data**

| % of full load | 100% | 80% | 60% | 40% |
|---|---|---|---|---|
| p2 (bar) | 1.180 | 1.178 | 1.178 | 1.180 |
| T2 (°C) | 11.2 | 11.6 | 11.8 | 12.1 |
| MF2 (m$^3$/h) | 34.3 | 30.5 | 27.1 | 24.2 |
| GA - $NO_x$ (ppm) | 15 | 13 | 14 | 19 |
| GA - CO (ppm) | 12 | 30 | 78 | 143 |
| MF7 (kg/s) | 4.3 | 4.3 | 4.3 | 4.3 |
| $P_{el,g}$ (kW) | 100 | 79.9 | 60 | 40 |
| $P_{el}$ (kW) | 95.0 | 74.9 | 55.0 | 35.0 |
| $P_{th}$ (kW) | 174.9 | 167.3 | 154.0 | 146.9 |
| $P_{fuel}$ (kW) | 382.4 | 338.9 | 301.3 | 269.1 |

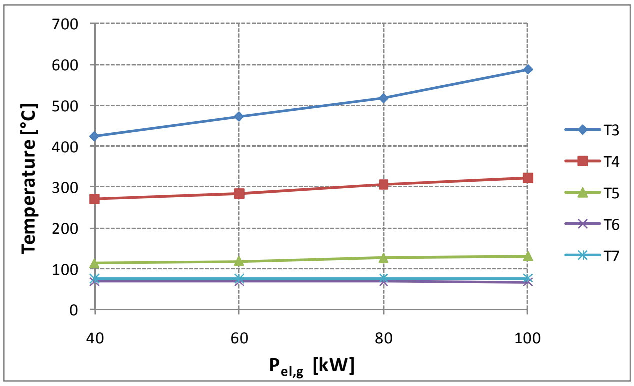


**Figure 3: Test in cogeneration mode. Measured temperatures as a function of $P_{el,g}$**

Trigeneration mode

The main experimental data of the trigeneration test (listed in Table 6) represents a typical operating day in the summer period. The main temperature trends are shown in Figure 4 and the thermal and electrical powers are calculated using the same equations employed for the cogeneration test.
The cooling power was calculated with the following equation:

$$P_c = \dot{m}_{air} \cdot \bar{\rho}_{air} \cdot (h_8 - h_9)$$

where $\dot{m}_{air}$ is the nominal volumetric flow rate of the treated air for the three units, which is equal to 15000 m$^3$/h; $\bar{\rho}_{air}$ is the average density of the treated air; $h_8$ and $h_9$ are the inlet and outlet enthalpy of the treated air, which is calculated according to psychrometric correlations [5].

**Table 6: Test in trigeneration mode. Main experimental data**

| % of full load | 100% | 80% | 60% | 40% |
|---|---|---|---|---|
| p2 (bar) | 1.175 | 1.175 | 1.175 | 1.175 |
| T2 (°C) | 23.8 | 22.4 | 23.8 | 23.8 |
| MF2 (m$^3$/h) | 35.0 | 31.9 | 28.1 | 25.0 |
| GA - $NO_x$ (ppm) | 23 | 19 | 20 | 23 |
| GA - CO (ppm) | 10 | 15 | 42 | 95 |
| MF7 (kg/s) | 3.5 | 3.5 | 3.5 | 3.5 |
| $P_{el,g}$ (kW) | 89 | 80 | 60 | 40.1 |
| $P_{el}$ (kW) | 84.0 | 75.1 | 55.0 | 35.1 |
| $P_{th}$ (kW) | 172.2 | 168.6 | 153.8 | 144.5 |
| $P_{fuel}$ (kW) | 363.4 | 341.4 | 298.8 | 266.2 |
| $P_c$ (kW) | 79.2 | 77.6 | 70.7 | 66.5 |

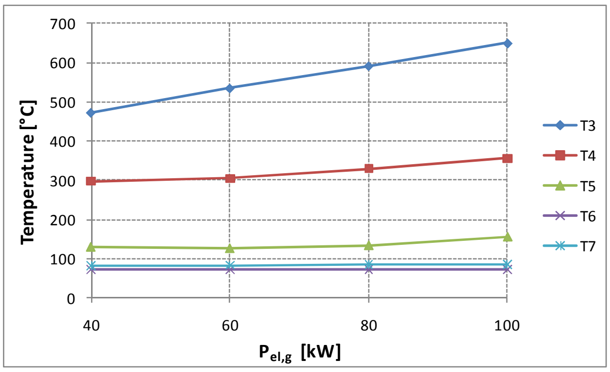


**Figure 4: Test in trigeneration mode. Measured temperatures as a function of $P_{el,g}$**

Sample trends of some daily data, regarding the operation of a desiccant unit at full load, are shown in Figure 5.

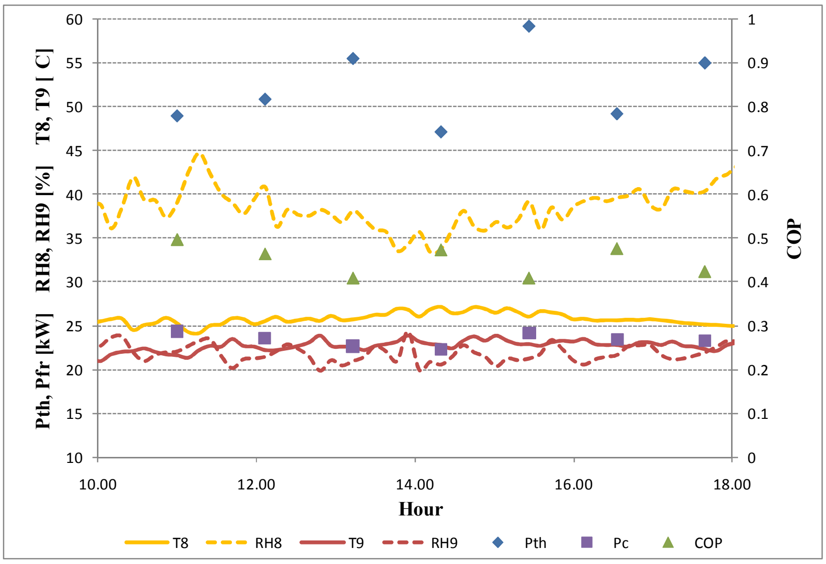


**Figure 5: Daily experimental data of a desiccant unit**

## Energetic analysis

The energetic analysis of the plant was based on the presented experimental data, both for cogeneration and trigeneration configuration tests and was carried out considering the plant operating for 1872 hours in winter (about 13 hours/day for 6 days/week, for 6 months) and 605 hours in summer (about 10 hours/day for 5 days/week, for 3 months) at different loads, according to three test cases defined as follows (see Figure 6):

- Case 1: operation at full load for all the time;
- Case 2: operation at full load for 70% of the time (both winter and summer) and at 80% of the full load for the remaining time;
- Case 3: operation at full load for 50% of the time (both winter and summer), operation at 80% of the full load for the 30% of time and operation at 60% of the full load for the remaining time.

The operating time of the plant is the same for all the cases and represents the need for partialization that may occur in small-scale CHCP, when there is a non optimal coupling of the plant capacity with the electrical and thermal load or in the case where the user load changes with respect to the nominal one. Cogeneration and trigeneration data sets have been used for the winter and summer periods, respectively.

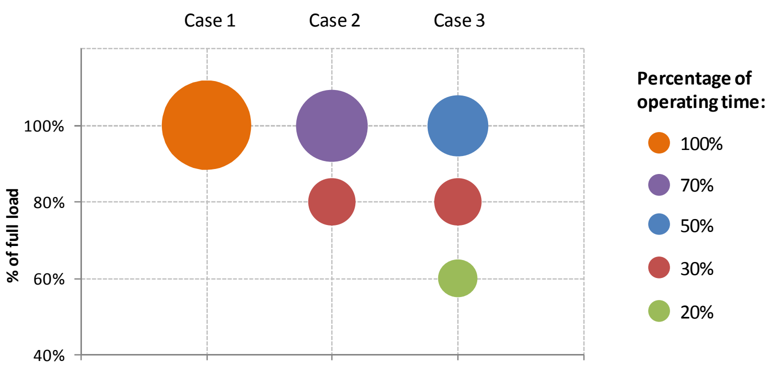


**Figure 6: Operating time and load for the three test cases**

The energetic performance of the plant in the three test cases was calculated by means of the PES (Primary Energy Saving) index [10]. This indicator is suggested by EU legislation and is defined by the following equation:

$$PES = 1 - \frac{E_{fuel}}{\frac{E_{el}}{\eta_{el,s}} + \frac{E_{th}}{\eta_{th,s}}} = 1 - \frac{1}{\frac{\eta_{el}^{eq}}{\eta_{el,s}} + \frac{\eta_{th}^{eq}}{\eta_{th,s}}} \quad \text{where} \quad \eta_{el}^{eq} = \frac{E_{el}}{E_{fuel}} \quad \text{and} \quad \eta_{th}^{eq} = \frac{E_{th}}{E_{fuel}}$$

A reference period of one year was considered in the calculations. $E_{fuel}$ is the total fuel energy input in the reference period; $E_{el}$ is the total electricity production of the microturbine and $E_{th}$ is the total thermal energy recovered from the prime mover, in the same reference period. $\eta_{th,s}$ and $\eta_{el,s}$ are the thermal and electrical efficiency values for the separate production [10]. The whole energetic production is considered fully self consumed.
With this formulation, all the heat employed in the summer season to produce a cooling effect can be considered as useful [11]: no cooling efficiencies of reference are in fact indicated. $\eta_{th,s}$= 0.9 and $\eta_{el,s}$ = 0.454 have been assumed as references in the calculations [10].
In Figure 7, the PES points obtained for each test case are represented in a plan where the X and Y axes are $\eta_{el}^{eq}$ and $\eta_{th}^{eq}$ respectively, as previously defined. The iso-PES lines have also been plotted.

As is well known, the analysis shows that the partial load operation strategy is energetically less convenient than the full load. The PES decreases from Case 1 (4.9%) to Case 3 (3.2%). The reduction in energy savings is due to the reduction in electric efficiency, which is typical of a cogenerator at partial load operation.

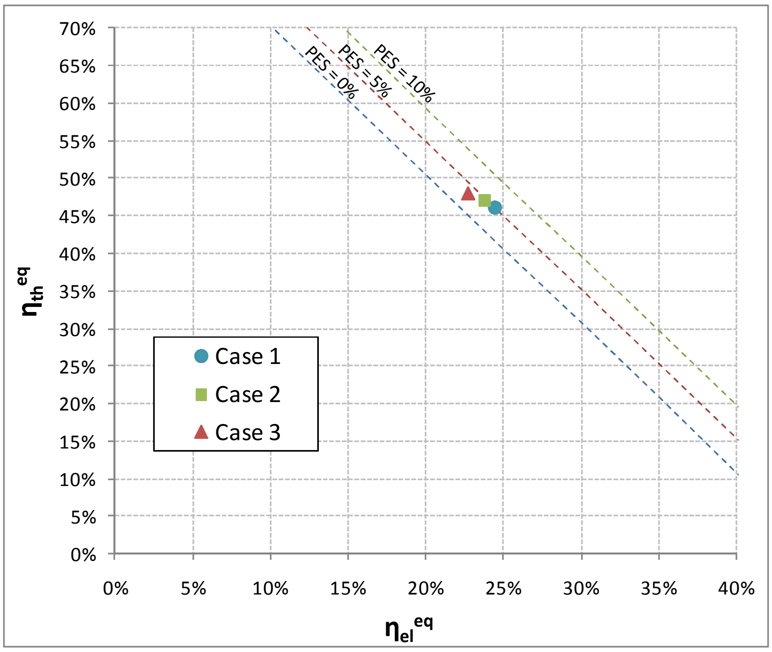


**Figure 7: PES points for the three Cases, with $\eta_{el,s}$ = 0.454 and $\eta_{th,s}$ = 0.9**

**Economic Analysis**

The convenience of operating a plant at partial load, following the electrical or the thermal load of the user, could be considered as a best practice to avoid energy waste. Nevertheless, this possibility needs to be investigated from an economic point of view, in order to assess the economic profitability of the operations. The following analysis, based on the three cases already discussed in the energetic section (see Figure 6), shows the calculation of the annual cash flow for the plant, through a determination of the revenues and costs [12].

Revenues

The revenues are constituted by the avoided costs of the electrical energy produced by the plant, the avoided costs of the electrical energy normally employed for the cooling production, and the avoided cost of the thermal energy recovered from the prime mover and exploited in winter for heating purposes (in place of the district heating service). An average price of the electrical energy has been considered, and has been calculated as the weighted average of the Politecnico di Torino prices for each time band in which the CHCP plant operates: F1 (Monday- Friday, from 8:00 to 19:00) and F2 (Monday – Friday from 7:00 to 8:00 and from 19:00 to 23:00; Saturday from 7:00 to 23:00).
Two costs have to be considered for each band: when the electricity produced by the plant is self-consumed, National and Regional taxes have to be paid nevertheless, while when an avoided purchase is considered (e.g. for cooling purposes in the summer season), tax expenses do not have to be taken into account.
A summary of all the electrical and thermal prices per unit is provided in Table 7.

Costs

The most important costs related to the operation of the system are the maintenance costs of the plants, the fuel, and the administration and operational costs (see Table 7).

**Table 7: Revenues and costs per unit**

| | |
|---|---|
| **Revenues** | |
| Electricity self consumption | 121.5 €/MWh |
| avoided purchase | 126.4 €/MWh |
| Thermal energy (from DH service) | 80.0 €/MWh |
| **Costs** | |
| Natural gas (with tax reduction) | 0.41 €/$Sm^3$ |
| Natural gas (without tax reduction) | 0.61 €/$Sm^3$ |
| Plant O&M | 14.0 €/$MWh_{el}$ |
| Plant administration costs | 3000 €/y |

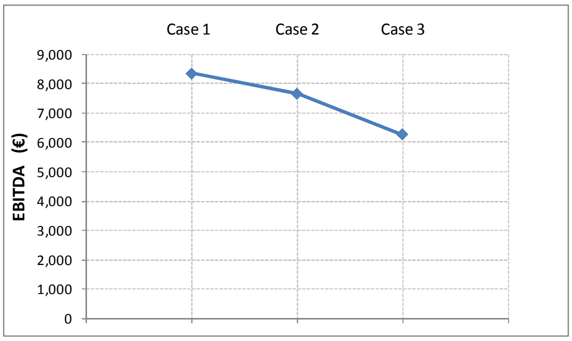


**Figure 8: EBITDA for the three cases**

The difference between the total revenues and the total costs for each test case represents the achievable Earnings Before Interest, Taxes, Depreciation and Amortization (EBITDA). The plots show that, even from the economic point of view, operation at partial load is less convenient than the full load strategy: the EBITDA decreases by about 25%, from Case 1 (8350 €/year) to Case 3 (6270 €/year).

**Conclusions**

The experimental data obtained from the operation of a small-scale CHCP plant, installed at the Politecnico di Torino, are shown in the paper. The sets of data refer to full load and partial load operations in both cogeneration and trigeneration plant configurations.

Three case studies have been presented and analyzed: in the first case (Case 1), the plant is operated at full load for a whole year. In Case 2, the full load operation is reduced to 70% of the total time and the remaining hours are operated at 80% of the rated power. In Case 3, half of the year is operated at full load, 30% of the time at 80% of the rated load and, for the remaining period, the plant is operated at 60% of the full load.

The PES index, suggested by the EU for energy performance assessment, has been determined and compared for the three cases. The analysis has shown that adopting a partial load strategy causes an energetic performance decrease. The Primary Energy Saving decreases from 4.9% in Case 1 to 3.2% in Case 2.

An economic analysis was also been carried out, and the EBITDA was determined for each case study. A slight decrease was noticed: the analysis has in fact shown how the EBITDA drops from 8350 €/year in Case 1, to 6270 €/year in Case 3.

As is well known, the preliminary analysis has shown that operating the plant at partial load is energetically and economically less convenient than at full load. Moreover, the technical datasheets report better energetic performances with respect to those calculated with the experimental data.

**Nomenclature**

| | |
|---|---|
| CHCP | combined heat, cooling and power plant |
| CHP | combined heat and power plant |
| COP | coefficient of performance |
| $c_p$ | specific heat capacity at constant pressure |
| DH | district heating |
| EU | European Union |
| EBITDA | earnings before interest, taxes, depreciation and amortization |
| GA | gas analyzer |
| MF | mass flow sensor |
| MGT | micro gas turbine |
| $\dot{m}$ | mass flow rate |
| PES | primary energy savings |
| TAT | thermally activated technology |
| $P_{el,g}$ | gross electrical power delivered by the prime mover generator |
| $P_{el}$ | electrical power delivered by the prime mover |
| $E_{el}$ | electrical energy produced by the prime mover |
| $P_{fuel}$ | fuel power delivered to the prime mover |
| $E_{fuel}$ | fuel energy introduced in the prime mover |
| $P_{th}$ | thermal power recovered from the CHCP plant |
| $E_{th}$ | thermal energy recovered from the CHCP plant |
| $P_c$ | cooling power delivered by the CHCP plant |
| PQ | power quality grid analyzer |
| p | pressure/pressure sensor |
| RH | relative humidity |
| T | temperature/temperature sensor |
| $\rho$ | density |
| $\eta_{el}$ | electrical efficiency of the prime mover |
| $\eta_{el,s}$ | electrical efficiency of the separate electricity production |
| $\eta_{th}$ | thermal efficiency of the CHCP system |
| $\eta_{th,s}$ | thermal efficiency of the traditional boiler for the separate production |

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