Operational analysis of natural gas combined cycle CHP plants: energy performance and pollutant emissions

Original
Operational analysis of natural gas combined cycle CHP plants: energy performance and pollutant emissions / Jarre, Matteo; Noussan, Michel; Poggio, Alberto. - In: APPLIED THERMAL ENGINEERING. - ISSN 1359-4311. - ELETTRONICO. - 100:(2016), pp. 304-314. [10.1016/j.applthermaleng.2016.02.040]

Publisher:
Elsevier

Published
DOI:10.1016/j.applthermaleng.2016.02.040

Operational analysis of natural gas combined cycle CHP plants: energy performance and pollutants emissions

Matteo Jarre, Michel Noussan, Alberto Poggio

Keywords: *natural gas combined cycle (NGCC), combined heat and power (CHP), operation, energy, emissions*.

Abstract

The natural gas-fired combined cycles (NGCC) plants are among the best technologies for power production, especially when operating in combined heat and power (CHP) generation feeding a district heating (DH) network. Even if usually designed to operate with very high utilization factors thus satisfying mainly the base load, nowadays these plant are often used also as backup power. This is due mainly to the necessity to compensate the non-programmable renewable energy sources (RES) production and it can be done thanks to the good flexibility of these plants. However, in off-design conditions the energy performance and the pollutants emissions may not be as good as the expected nominal ones. In this paper, the real operation of three NGCC units has been analysed in detail by considering mean hourly data over several years. A gas turbine efficiency curve at partial loads has been obtained, showing a decrease of conversion efficiency at lower unit loads. The CO emissions during the start-up and shut-down procedures of the plant reached values that are some orders of magnitude higher than in normal operation. This criticality should not be forgotten when using these units for frequent on-off operations.

Nomenclature

CEMS	Continuous Emissions Monitoring System
CHP	Combined Heat and Power
DH	District Heating
NGCC	Natural Gas-fired Combined Cycle
RES	Renewable Energy Sources
SCR	Selective Catalytic Reduction

Introduction

The efficiency of the energy conversion plants is among the main topics discussed in EU energy policies [1]. Various advantages are related to an increase of the conversion efficiency, from climate change mitigation to decrease of overall fossil fuels consumption, with both environmental and geo-political concerns [2]. Considering fossil fuels, the natural gas-fired combined cycle (NGCC) plants are currently among the best available technology in terms of conversion efficiency [3], especially when operating in combined heat and power (CHP) mode [4]. The cogeneration in NGCC plants often requires the connection to a district heating (DH) network, as the connection to industrial users is often hindered by the large size of these units, resulting in high available heat. This configuration is among the most efficient solutions for providing heat to buildings [5]. A state-of-the-art NGCC plant can reach up to 58% of electrical efficiency and 90% of global conversion efficiency [6].

Due to these reasons, a number of NGCC have been built in last decades, resulting in an increase of the electricity production efficiency from natural gas. However, the operation of these plants is currently facing significant transformations, mainly due to the increase of the share of electricity production from renewable energy sources (RES) [7], [8]. The EU targets on RES production by 2020 [9] resulted in a spread of RES electricity plants, especially photovoltaics, wind and biomass plants. The increase of RES share in Italian Power Market (IPEX), up to 38% of National electricity production in 2014 [10], resulted in a global decrease of average market prices [7], [11]. This situation had a significant impact on fossil-fuel based generation, as the plants that were not able to cope with the new prices have been shut down. Considering NGCC, the ones coupled to a DH network can mitigate the electricity price decrease thanks to the heat sales incomes. Anyway, the new units commitment cannot leave aside the new market scenario, and alternative commitment models need to be studied and developed [12], [13].

Another significant aspect of the new market situation is the high variability of production conditions: solar and wind power are intermittent and non-programmable, that possibly resulting in very different energy mixes in the same day. A significant amount of backup power is then needed to guarantee the network stability: as a result, NGCC are often chosen as backup plants rather than simple power generation plants thanks to their quick start-up and shut-down. However, these transitory operations may have an impact on energy performance and pollutant emissions. An operation analysis needs to be carried out with detailed time step, to consider the real conditions of the generation plant, which can significantly differ from the nominal conditions and have steep and quick variations that could not be highlighted when using time-aggregated data.

In this paper, an operational analysis has been performed on two different NGCC CHP plants, both connected to the same DH network, in the city of Turin (Italy). The study considers both energy performance and pollutants emissions, focusing on CO, NO_X and NH_3, which are the most critical emissions associated with this technology (NH_3 emissions being caused by the SCR flue gases cleaning systems). This paper shows some preliminary results, which will be the basis for further analyses and comparisons with other CHP systems.

Case Study

Three different CHP units are used as case studies in the present work; two of these, named in the following “2GT” and “3GT”, are installed in the “Moncalieri” plant, located in Moncalieri, a small town close to Turin, Italy. The third unit, named in the following “TON”, is installed in the “Torino Nord” plant located in the northern zone of Turin. Both these plants are owned and operated by the same company and they both feed the existing DH network of the city of Turin. The Moncalieri plant has been renovated several times and it has been operative in its current configuration from 2008; the Torino Nord plant, on the other hand, has been built in 2011 to be coupled with the extension of the DH network in the northern zone of Turin.

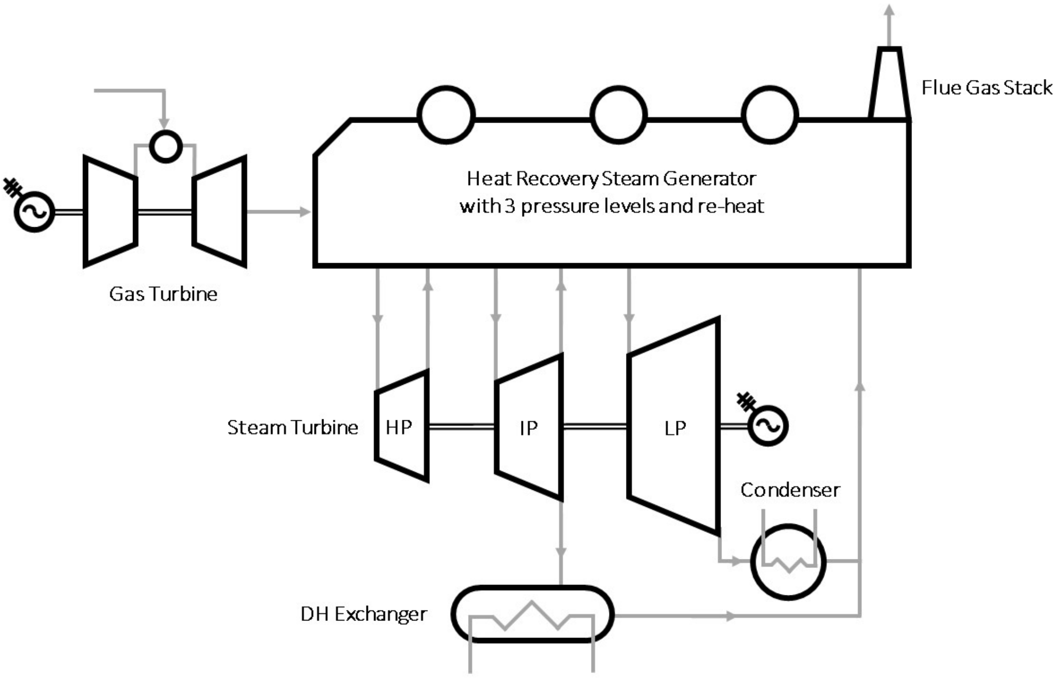

Figure 1 – General configuration scheme for the three considered units (elaboration from [14], [15], [16]).

Table 1 summarizes the main technical data of the three considered units.

Table 1 - Main technical components and data of the three analysed units (data from [14], [15] and [16]).

Plant Component	**Value**	**Moncalieri Plant**		**Torino Nord Plant**
		2GT	**3GT**	**TON**
Gas Turbine	**Nominal Gross Electric Power (MW)**	270	260	270
	Fuel	natural gas	natural gas	natural gas
Heat Recovery Steam Generator (High / Medium / Low Pressure Stages)	**Pressure (bar)**	94 / 28 / 4,6	104 / 28 / 3,5	125 / 30 / 4,5
	Temperature (°C)	542 / 542 / 225	550 / 560 / 250	550 / 550 / 237
Steam Turbine	**Nominal Gross Electric Power (MW)**	141	138	119
District Heating Heat Exchangers	**Nominal Thermal Power (MW)**	260	260	220
	Inlet Temperature (°C)	70	70	70
	Outlet Temperature (°C)	120	120	120
Condenser	**Cooling Fluid**	Water	Water	Air
Combined Cycle Operation (ISO conditions on site)	**Net Electric Power (MW)**	395	383	390
	Global Efficiency (-)	58%	57%	56%
Combined Cycle + Cogeneration Operation (ISO conditions on site)	**Net Electric Power (MW)**	340	322	340
	Thermal Power (MW)	260	260	220
	Global Efficiency (-)	90%	87%	87%

Figure 1 and Table 1 report the current configuration for the three CHP units in terms of main component of thermal-electrical groups. It can be seen that 2GT and 3GT units have identical configuration schemes, with 2GT group having slightly higher values of nominal electric power for both gas and steam turbines (this is due to the later renovation of this group with respect to the 3GT one). The TON unit has both lower electric nominal power for the steam turbine and lower thermal power of the heat exchanger that feeds the district heating network. The most peculiar feature of this unit is the adoption of an air-cooled condenser in lieu of the usually adopted water-cooled condenser.

Each of the studied units is equipped with a Continuous Emissions Monitoring Systems (CEMS) that acquires and records several values regarding both plant energy production and emissions, among which:

- Pollutants mass concentration (mg/Nm^3) within flue gases (referred to O_2 15%$_{vol}$)
    - Carbon monoxide CO
    - Nitrogen oxides NO_X calculated as equivalent NO_2
    - Ammonia NH_3
    - Total Suspended Particles (TSP)
- Flue gases output characteristics
    - Oxygen volumetric concentration (%$_{vol}$) within flue gases
    - Water volumetric concentration (%$_{vol}$) within flue gases
    - Flue gases temperature (°C)
    - Flue gases pressure (hPa)
    - Flue gases volumetric flow rate (thousands of Nm^3/h)
- Electric and thermal energy production
    - Natural gas input flow rate (Sm^3/h)
    - Gas turbine gross electric power output (MW)
    - Total (gas turbine + steam turbine) gross electric power output (MW)
    - Thermal power output to the district heating network (MW)
- Operational state of the unit (regular service, start-up / shut-down, stoppage)

All the records are available as mean hourly values for specific periods:

- Moncalieri plant (2GT and 3GT units): January 1st, 2010 – July 31st, 2015
- Torino Nord plant (TON unit): June 17th, 2013 – July 31st, 2015

All the records are coupled with an ID percentage calculated as the fraction of that specific hour for which the value has been recorded; this indicator is therefore used as an availability/reliability index for each value. The records are published on an online database freely accessible, as required by the Public Authority for these generation plants.

Methodology

Literature about NGCC plants is filled with information about their design, optimization processes and theoretical formulations to determine several parameters. Nevertheless, few information is usually provided about real operation of these plants and little analysis has been carried to determine whether real world conditions usually allow for optimal use of CHP technologies. Furthermore, few real data analysis is currently available about NGCC based CHP plants pollutant emissions; in particular, very little is known about the efficiency and the pollutants emission levels of these plants when operating with frequent load variations, as it is more and more common for large-sized plants that are competing with renewable electricity sources.

The main objective of this work is to present real operational data of three different existing NGCC based CHP units. The data have been collected from the existing CEMS and elaborated in order to analyse the existence of regular trends and correlations among different data; furthermore, the compliance between the most used theoretical formulation about the operation of NGCC and the effective data will be investigated.

In addition, the availability of hourly data allows operating interesting comparisons among the different time-steps at which data could be analysed; in particular, it will be highlighted how the use of simple mean yearly data does not allow precisely identifying peculiar behaviours of the analysed units.

Finally, the availability of a long period based dataset allows for the effectiveness evaluation of some plant modifications that have occurred during the units' operational life.

The efficiencies of the analysed units have been defined in terms of different parameters:

- Gross electric efficiency of the gas turbine ($\eta_{el,GT}$), defined as the ratio between the gross electric power output of the gas turbine ($P_{el,GT}$) and the total energy entering as fuel, calculated as the product between the mass flow rate ($\dot{m}_{NG}$) and the LHV (LHV_{NG}) of natural gas. Since the latter is a value that depends on both the period and location at which natural gas is delivered, no constant value was used; instead, monthly values of LHV were used referenced to the delivering zone that corresponds to the location of Moncalieri from the database of the Italian natural gas pipelines operator (see [17]). These data were available for all the considered years except 2010, for which a constant value was used for every month.

$$\eta_{el,GT} = \frac{P_{el,GT}}{\dot{V}_{NG} * LHV_{NG}} \ (-)$$

- Gross global efficiency ($\eta_{el,gl}$) defined as the ratio between the total gross electric power output from both gas and steam turbines ($P_{el,GT+ST}$) and the total energy entering as fuel (see above).

$$\eta_{el,gl} = \frac{P_{el,GT+ST}}{\dot{V}_{NG} * LHV_{NG}} \ (-)$$

- Fuel Utilization efficiency (FUE) calculated by dividing the total production (i.e. the sum of total gross electric power and the thermal power to the DH network) by the total energy entering as fuel (see above).

$$FUE = \frac{P_{el,GT+ST} + P_{DH}}{\dot{V}_{NG} * LHV_{NG}} \ (-)$$

- Gas turbine load, defined as the ration between the gross electric power output and the nominal electric power output ($P_{el,GT,nom}$) of the gas turbine. This load represents the fraction of the total electric capacity of the gas turbine that is effectively used at every time-step.

$$l_{GT} = \frac{P_{el,GT}}{P_{el,GT,nom}} \ (-)$$

The operation of CHP plants is characterized by the necessity to find an equilibrium between the electricity and the heat production; this equilibrium is defined into the so-called "Power to Heat" graph in which thermal and electric power produced by the NGCC unit are represented on the two axis (see Figure 2). All the operational points of the system are comprised within the given area; each point represent one possible couple of combined heat and power production by the NGCC. The sum of these two contributions depends of course on the total heat that is delivered to the steam turbine by the exhausts of the gas turbine; the different loads of the gas turbine are therefore represented through the sloped lines.

The slopes of the lines corresponding to the different loads of the gas turbine represent a fundamental parameter for the evaluation of the performances of a NGCC plant: the *power loss factor* expresses the loss in power production due to the production of heat in substitution [18]. This parameter is valid for NGCC plants in which heat production decreases power production because of the steam extraction from the steam turbines. For plants connected to DH networks this parameter ranges between 0.15 and 0.3 at full load of the gas turbine [4]; as an example the graph for the 2GT unit is reported in Figure 2 and the corresponding power loss factor is calculated. Its value is equal to about 0.23 / 0.21 / 0.11 respectively at 100% / 75% / 45% of the gas turbine load.

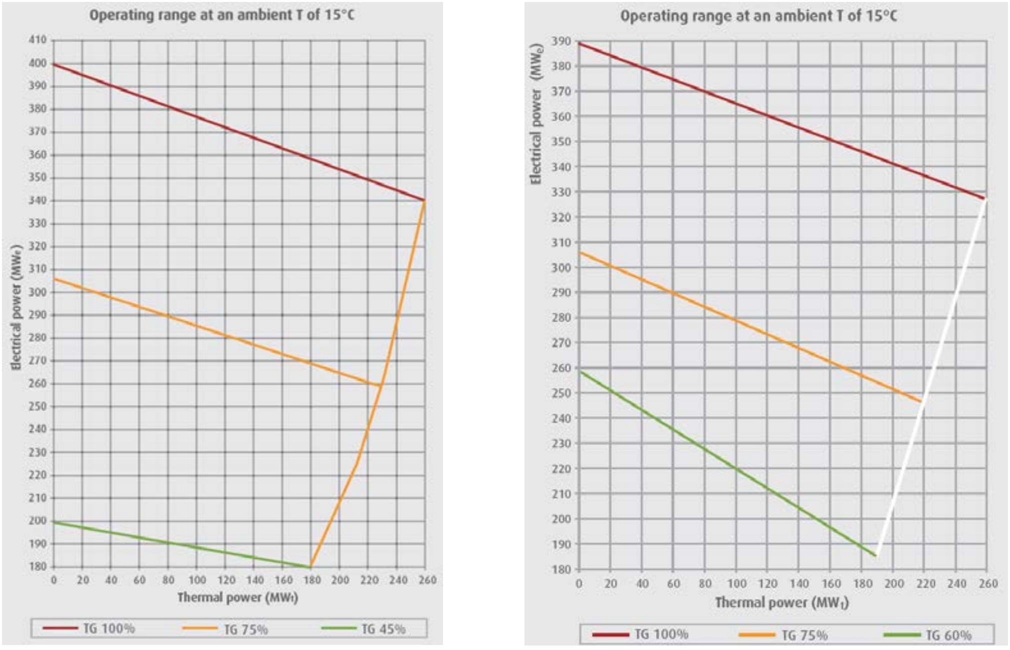

Figure 2 - Power to Heat graph for the 2GT and 3GT units.

In this work, such graph is recreated using real operation data and a comparison is provided with the theoretical graphs available for the analysed units.

Finally, different pollutants emissions data were studied. In particular, it is possible to analyse the trend in time of the emission levels thus highlighting the very different emission factors of the different plants when the load varies consistently. This is of primary importance since available data are usually regarding steady-state operation only and neglecting any emission contribution during start-ups and shut-downs, whose emission factors are significantly higher.

In Table 2, the limits prescribed by law and authorised for each of the analysed units are reported (see D.Lgs. 152/06). For the two units located in Moncalieri, such limits have been lowered for NO_X after summer 2014 because of the expected installation of two $DeNO_X$ Selective Catalytic Reduction systems. A provision for such system was installed during the construction of the 2GT unit, while no provision was made within the 3GT unit structure; in the latter, the SCR system has then a smaller size and non-optimal positioning. For this reason, new NO_X limits for the 2GT unit are stricter with respect to those of the 3GT unit. A DeNOx SCR unit has been installed since the beginning of operations into the Torino Nord Plant, whose emission limits have therefore been never varied.

Table 2 - Mean hourly emission legal limits for the three analysed units (from [19] and [20]).

Plant / Unit	**CO (mg/Nm³)**	**NO_X (mg/Nm³)**	**Flue gases treatment systems**
Moncalieri / 2GT	10	50 (1) 10 (2)	SCR, CO oxidation
Moncalieri / 3GT	10	50 (1) 35	SCR, CO oxidation
Torino Nord / TON	10	10	SCR, CO oxidation
Notes:			
(1): Until August 20th, 2014			
(2): 6 months after the installation of the SCR unit; for the first 6 months the limit has to be considered on a daily basis only			

Results and discussion

Energy performance

The operational analysis of the system starts from the energy performance. Table 3 shows a synthesis of the annual operation of the CHP units considered in this study (data from [19] and [20]). While for the units installed in Moncalieri there are five entire years of operation, considering the Torino Nord unit the available data are less extended: the commercial operation began in May 2012, and the data for the entire year 2014 have not been published in any official document by the Plant operator.

All the units show an average annual electric efficiency around 50%, with some fluctuations from year to year due to different operation conditions. Likewise, the total efficiency is around 70%, being generally lower for the Torino Nord unit, due to a lower production of useful heat with respect to the other NGCC units.

Table 3 – Annual operation of CHP units: energy production, natural gas consumption and average efficiencies (data from [19] and [20], and calculations of the authors).

Moncalieri - 2GT			**2010**	**2011**	**2012**	**2013**	**2014**
Gross electricity production	$E_{el,gross}$	*GWh*	1,919	2,264	1,669	2,029	1,585
Useful heat production	E_{th}	*GWh*	757	730	660	751	818
Natural gas consumption [1]	E_{fuel}	*GWh*	3,723	4,312	3,280	3,990	3,264
Annual electric efficiency	$\eta_{el,gl}$	-	51.5%	52.5%	50.9%	50.8%	48.6%
Annual fuel utilization efficiency	AFUE	-	71.9%	69.4%	71.0%	69.7%	73.6%

Moncalieri - 3GT			**2010**	**2011**	**2012**	**2013**	**2014**
Gross electricity production	$E_{el,gross}$	*GWh*	2,074	2,155	1,941	1,941	1,093
Useful heat production	E_{th}	*GWh*	797	842	968	1,067	735
Natural gas consumption [1]	E_{fuel}	*GWh*	4,035	4,209	3,911	3,941	2,295
Annual electric efficiency	$\eta_{el,gl}$	-	51.4%	51.2%	49.6%	49.3%	47.6%
Annual fuel utilization efficiency	AFUE	-	71.2%	71.2%	74.4%	76.3%	79.7%

Torino Nord - TON			**2010**	**2011**	**2012** [2]	**2013**	**2014** [3]
Gross electricity production	$E_{el,gross}$	*GWh*	-	-	792	1,894	569
Useful heat production	E_{th}	*GWh*	-	-	164	442	211
Natural gas consumption [1]	E_{fuel}	*GWh*	-	-	1,554	3,708	1,161
Annual electric efficiency	$\eta_{el,gl}$	-	-	-	51.0%	51.1%	49.0%
Annual fuel utilization efficiency	AFUE	-	-	-	61.5%	63.0%	67.2%

[1] based on a heating value of 9.76 kWh/Sm3

[2] from 30/04/2012 (first day of commercial operation)

[3] first semester 2014

Considering hourly data, Figure 3 and Figure 4 show some typical power and heat loads of the Moncalieri – 2GT unit, representing a winter period and a summer period. The charts show the gas turbine gross power production, the steam turbine gross power production as well as the heat supplied to the DH network.

Considering Figure 3, which refers to a winter week, the heat production is clearly varying from daytime to night-time, depending on the users' consumption profile. Different operational logics can be observed in these charts. In the last days of the week (14th and 15th) the gas turbine load seems to be controlled following the heat profile. On the other hand, in the first days of the week, the gas turbine has a more stable operation, and consequently the power production from steam turbine increases at night, when less heat is required by the DH network.

Figure 3 – Example of power and heat loads for Moncalieri 2GT in February 2015.

Figure 4 shows a typical summer week in which, of course, the heat demand of the DH system is considerably lower. However, a certain amount of heat is still required to keep the network working to provide some domestic hot water to particular users; this requires of course also to feed enough heat to exceed the network heat losses. Moreover, in summer the heat demand is entirely supplied by the NGCC units, whereas in winter the peak power is provided by auxiliary boilers and heat storage systems. In general, at summer time the two units are seldom in simultaneous operation, due to maintenance needs and lower economic profitability (especially with lower prices caused by high RES production in summer).

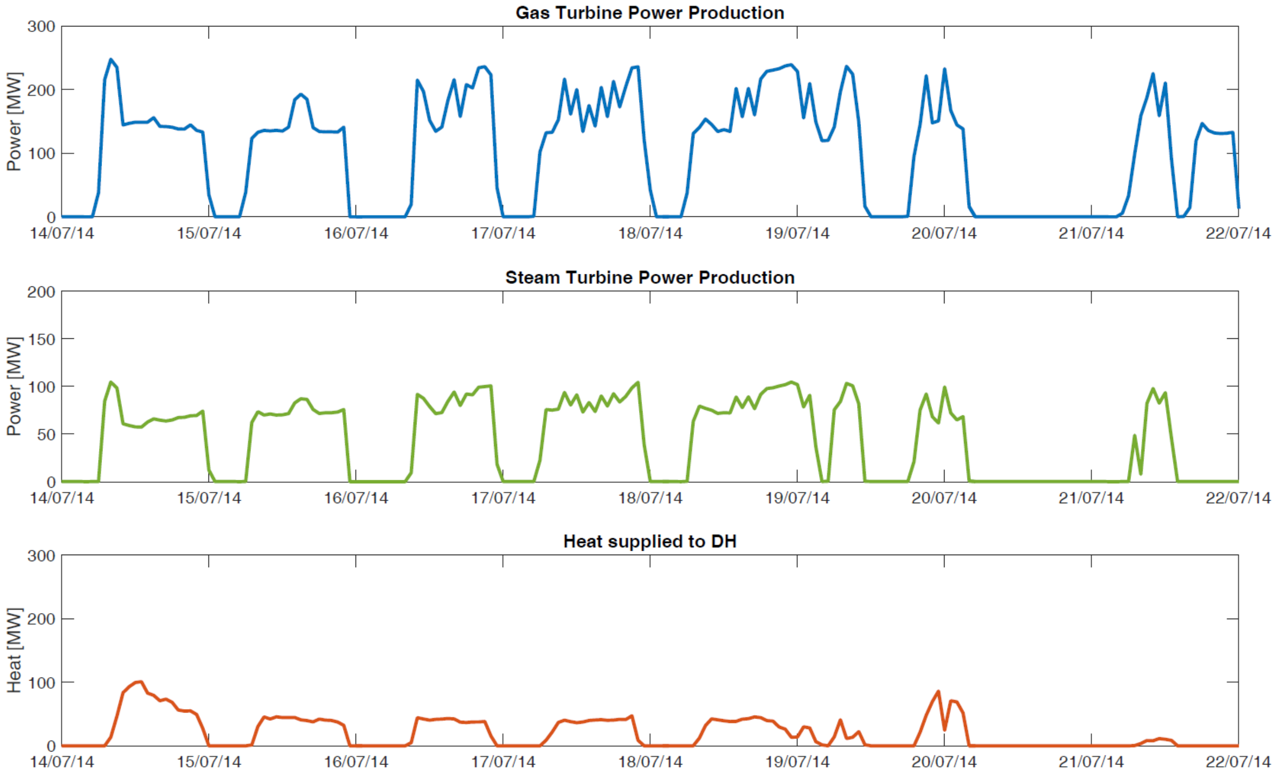

Figure 4 – Example of power and heat loads for Moncalieri 2GT in July 2014.

Thanks to the availability of a considerable amount of data, the calculation of the gross electric efficiency of the gas turbine at different loads has been obtained with a linear correlation between the fuel consumption and the gross output power. The results are shown in Figure 5, providing a good correlation between the curve and the actual data. The chart shows similar behaviours for the three gas turbines, with some slight differences related to the characteristics of each unit and to the different operation conditions that occurred over the years. The vertical oscillations are probably connected to different environmental operation conditions.

The gross output power produced by each NGCC plant, including the electricity produced by gas turbine and steam turbine, can be analysed in relation to the required input fuel and the heat supplied to DH system. Figure 6 shows an example for Torino Nord plant, where the loss of power related to the steam drain for DH heat supply can be noticed. The linear behaviour of the trends represents a good electric efficiency even at partial loads.

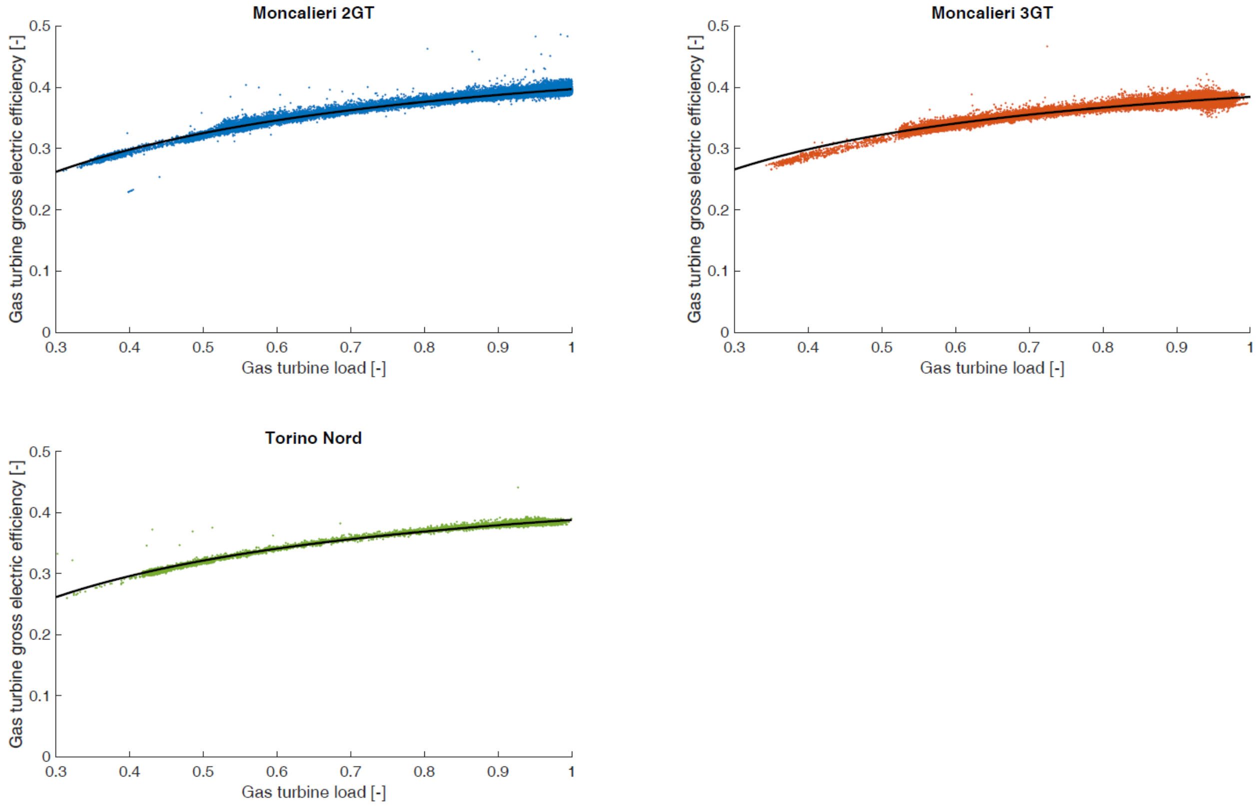

Figure 5 – Gas turbines efficiency at partial load.

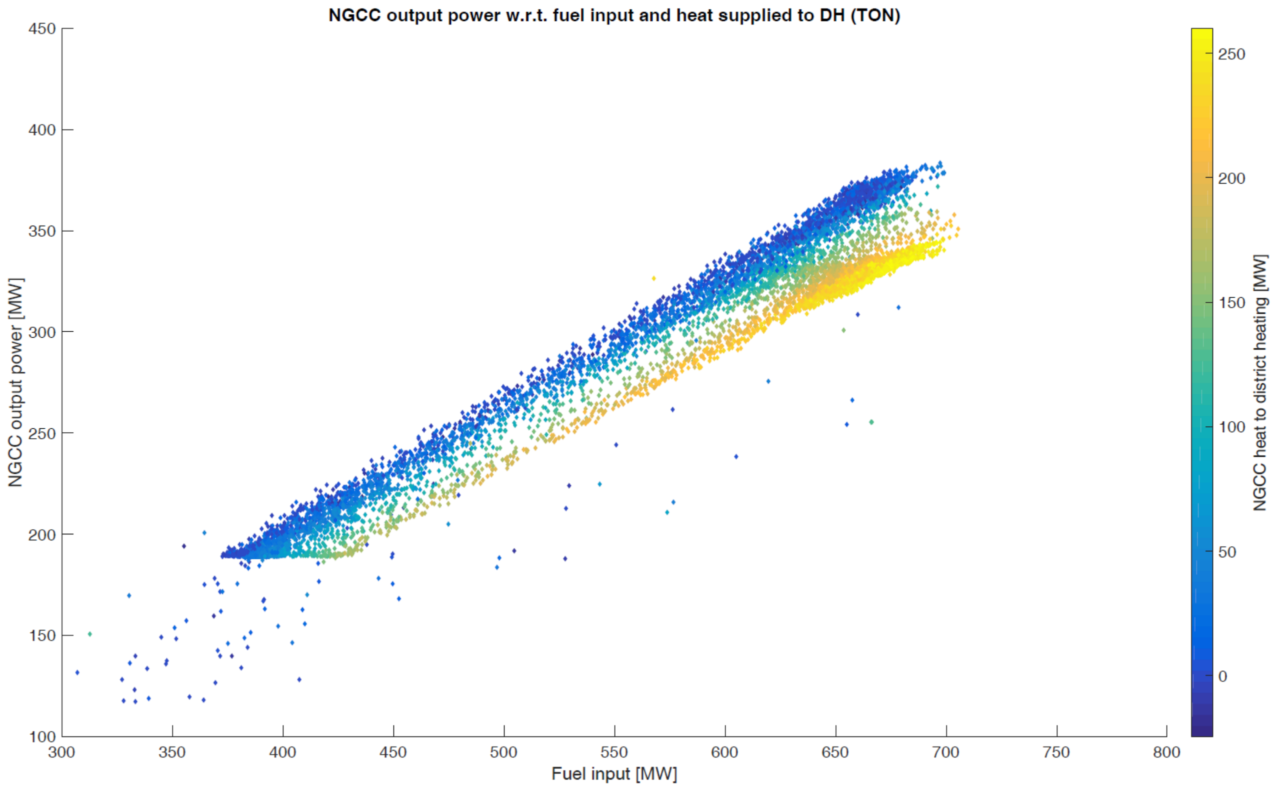

Figure 6 – NGCC output power w.r.t. fuel input and heat supplied to DH (2GT).

Another interesting analysis regards the possibility of drawing the Power/Heat diagram, in order to compare the actual NGCC behaviour with the reference operation conditions at 15°C provided by the manufacturer (available in [14] and [15]). The results obtained for 2GT and 3GT units are reported in Figure 7 and Figure 8. The grey lines show the expected NGCC behaviour in standard conditions at different turbine loads.

The chart shows that the plant is often operated over 80% of electric load (red points), at different levels of heat output depending on the network demand. While there is some partial operation with low heat outputs, the chart suggests that when less heat is required the plant still runs at full power, using the available steam to supply the steam turbine instead of lowering the gas turbine load.

These charts show that during real operation the power output tends to be relatively constant for a given load (see the horizontal points trends, especially at partial loads); this behaviour is unforeseen since at reference conditions power output is expected to increase when heat production decreases. This behaviour is probably due to the Italian electricity market structure; in particular, it can be associated to the constant amount of power supplied to the network, which is set by previous deals of power supply. As a result, the NGCC units seem not operating at their best efficiency with respect to nominal performance curves.

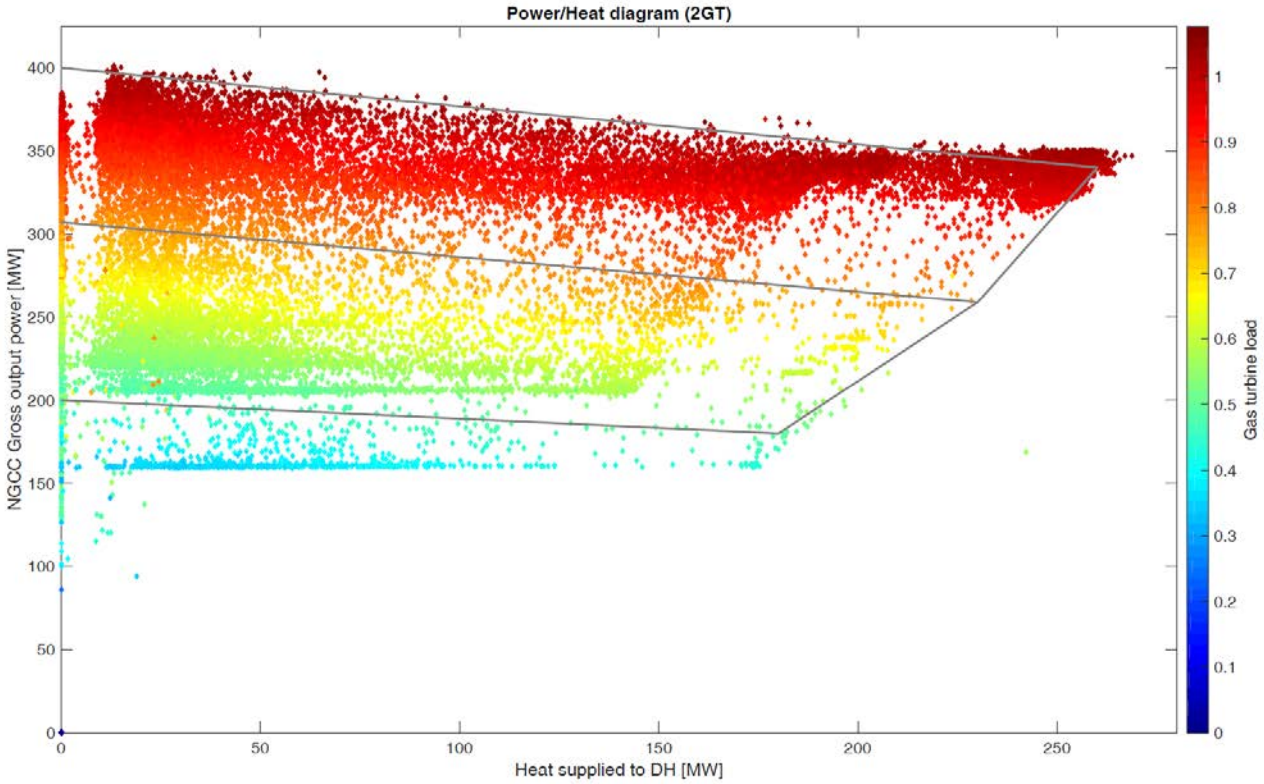

Figure 7 – Power/Heat diagram for Moncalieri 2GT, reference operation conditions @ 15°C shown in grey (see Figure 2).

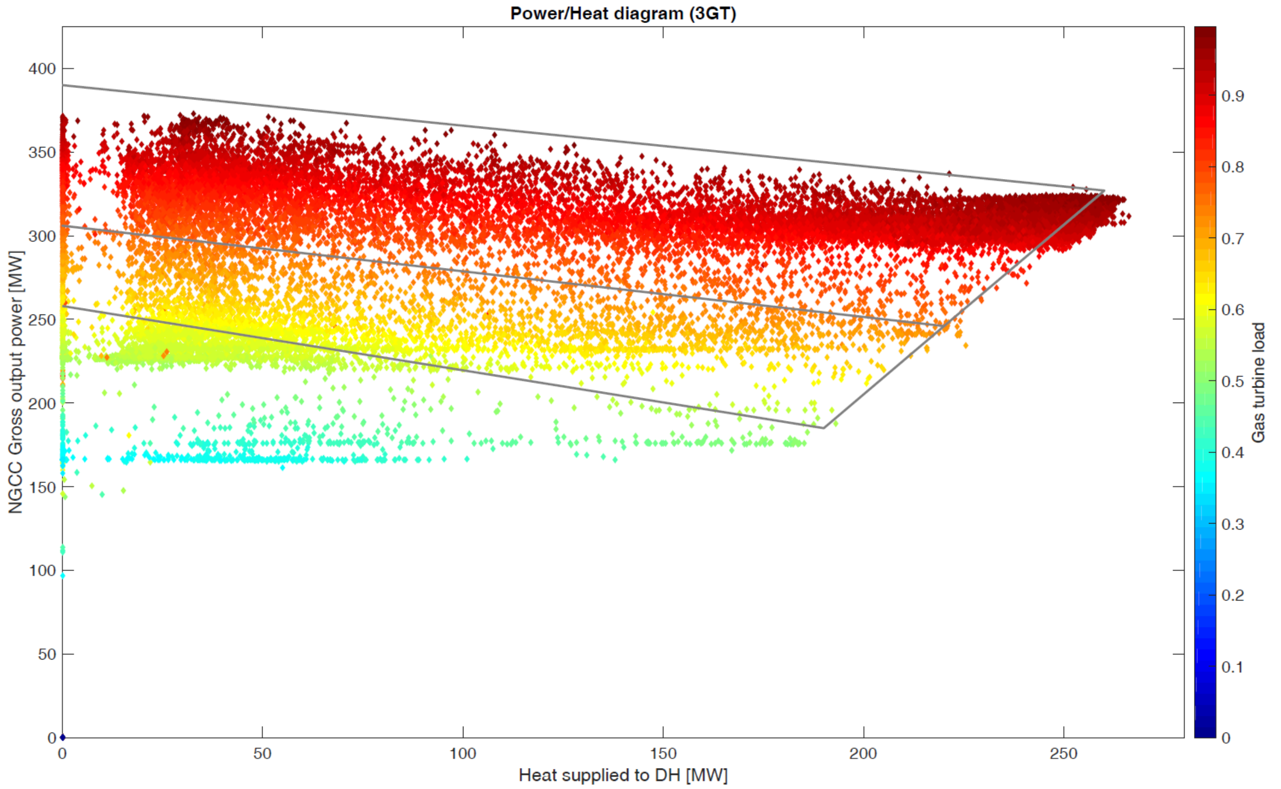

Figure 8 – Power/Heat diagram for Moncalieri 3GT, reference operation conditions @ 15°C shown in grey (see Figure 2).

The results presented in the charts above show a good performance of the systems over the years, considering that the actual operation of complex systems needs to face many different conditions. As a result, the energy performance is affected by the operational logics and the control strategies chosen by the plant manager, which are often related to other aspects (e.g. technical feasibility, economic profitability, reliability concerns, etc.).

Pollutants emissions

The emission factors for Moncalieri and Torino Nord CHP plants are shown in Table 4. The emission factors are calculated by dividing the total emissions by the gross electricity production. The emission factors considered are related to CO_2, NO_X and CO. These values have been compared with the performance of other Italian NGCC plants operating in non-CHP mode (public data of ten power plants referring to years 2011-2013).

The carbon dioxide emissions are related only to the conversion efficiency of the plants, and the decrease of the emission factor over the years is caused by a decrease of the specific natural gas consumption of the gas turbines. The other Italian NGCC plants considered in this analysis show a range of emissions of 363.5 ÷ 426.9 t/GWh_{el}, with an average value of 388.3 t/GWh_{el}. These plants, operated in non-CHP mode, have therefore a slightly higher electrical efficiency, resulting in lower specific emissions.

The NO_X emission factor in Moncalieri is stable over the years, with a little decrease for 2014, caused by the installation of two SCR gas-cleaning systems in the second semester of 2014. The emissions of Torino Nord plant are much lower, as the SCR system has been installed since the beginning of the plant operation. The other Italian NGCC plants considered in this analysis show a range of emissions of 0.051 ÷ 0.203 t/GWh$_{el}$, with an average value of 0.106 t/GWh$_{el}$.

The CO emission factor is the most different between the two power plants, and it is mainly related to the operation strategy of the plants. The more frequent the plant's start-up and shut-down, the higher the CO emissions. Both plants need to face an increased need of variable load depending on the electricity market conditions, and for Torino Nord this aspect is more critical and leads to higher emission factors in recent years. The other Italian NGCC plants considered in this analysis show a range of emissions of 0.003 ÷ 0.314 t/GWh$_{el}$, with an average value of 0.040 t/GWh$_{el}$, considering the years 2011-2013, which had different market conditions than 2014 (where a large increase of specific emissions in Moncalieri and Torino Nord can be observed).

Table 4 – Main emission factors of Moncalieri and Torino Nord CHP plants.

Moncalieri (2GT and 3GT)		**2010**	**2011**	**2012**	**2013**	**2014**
CO_2 emission factor	t/GWh$_{el}$	393.2	386.5	398.1	396.5	412.6
NO_X emission factor	t/GWh$_{el}$	0.133	0.125	0.136	0.145	0.122
CO emission factor	t/GWh$_{el}$	0.009	0.006	0.036	0.103	0.160

Torino Nord		**2010**	**2011**	**2012**	**2013**	**2014**
CO_2 emission factor	t/GWh$_{el}$	-	-	384.8	393.1	411.6
NO_X emission factor	t/GWh$_{el}$	-	-	0.037	0.039	0.058
CO emission factor	t/GWh$_{el}$	-	-	0.474	0.214	0.693

As discussed above, the main pollutants associated with NGCC are CO and NO_X, which are continuously monitored. With the use of SCR cleaning systems, the NH_3 emissions are usually monitored too.

The CO specific emissions are strongly dependent on the gas turbine load, becoming very critical during the start-up and shut-down phases of the plant. The Figure 9 shows that the specific CO emissions are decreasing with the plant load, and are usually under the limit of 10 mg/Nm^3 during the normal operation. At start-up and shut-down, however, the emissions become several orders of magnitude higher, reaching up to 7,000 mg/Nm^3. This aspect is particularly critical for Torino Nord plant, as already discussed above.

Considering NO_X emissions, the behaviour of each NGCC unit appears to be different. With reference to Figure 10, the 3GT has the worst performance, showing specific emissions in the range from 15 to 40 mg/Nm^3. The Torino Nord unit, equipped with a SCR filter since the beginning of its operation, shows specific emissions as low as 5 mg/Nm^3, and always lower than its limit of 10 mg/Nm^3.

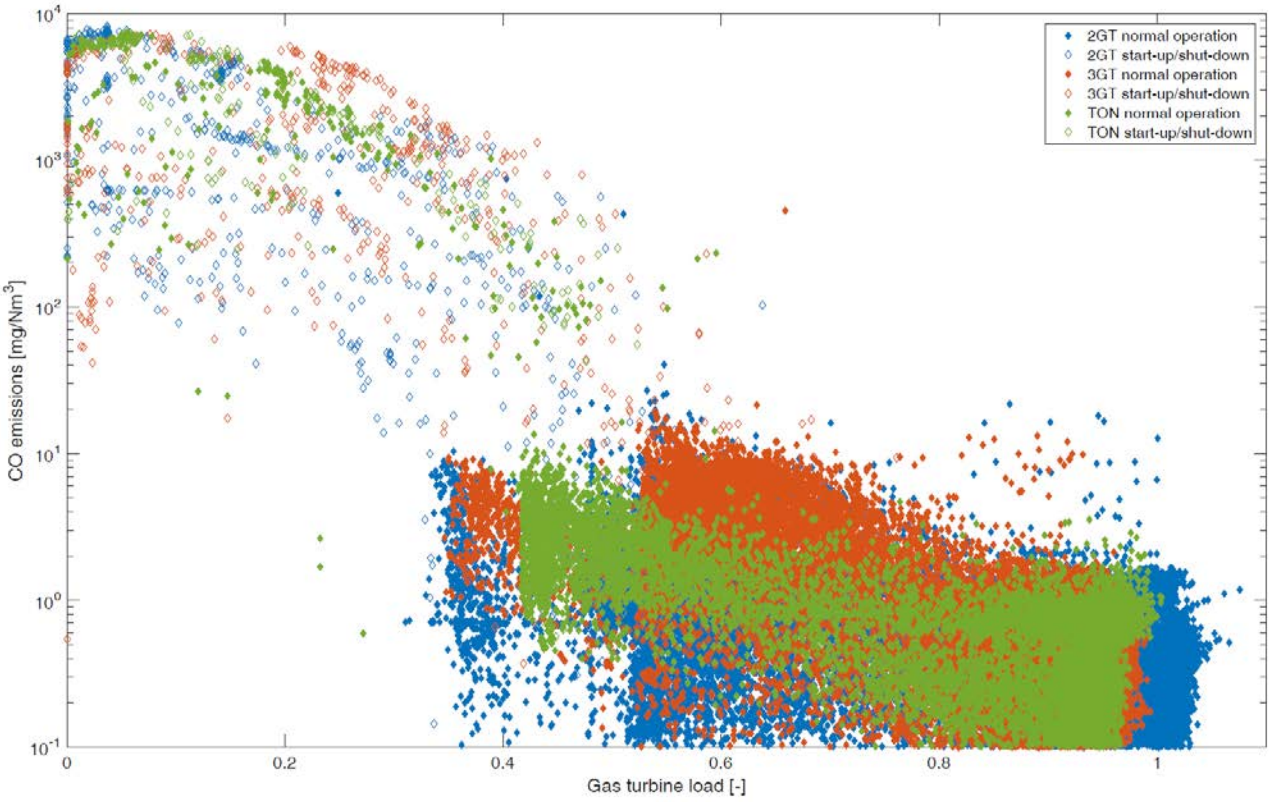

Figure 9 – Specific CO emissions for each unit w.r.t. gas turbine load.

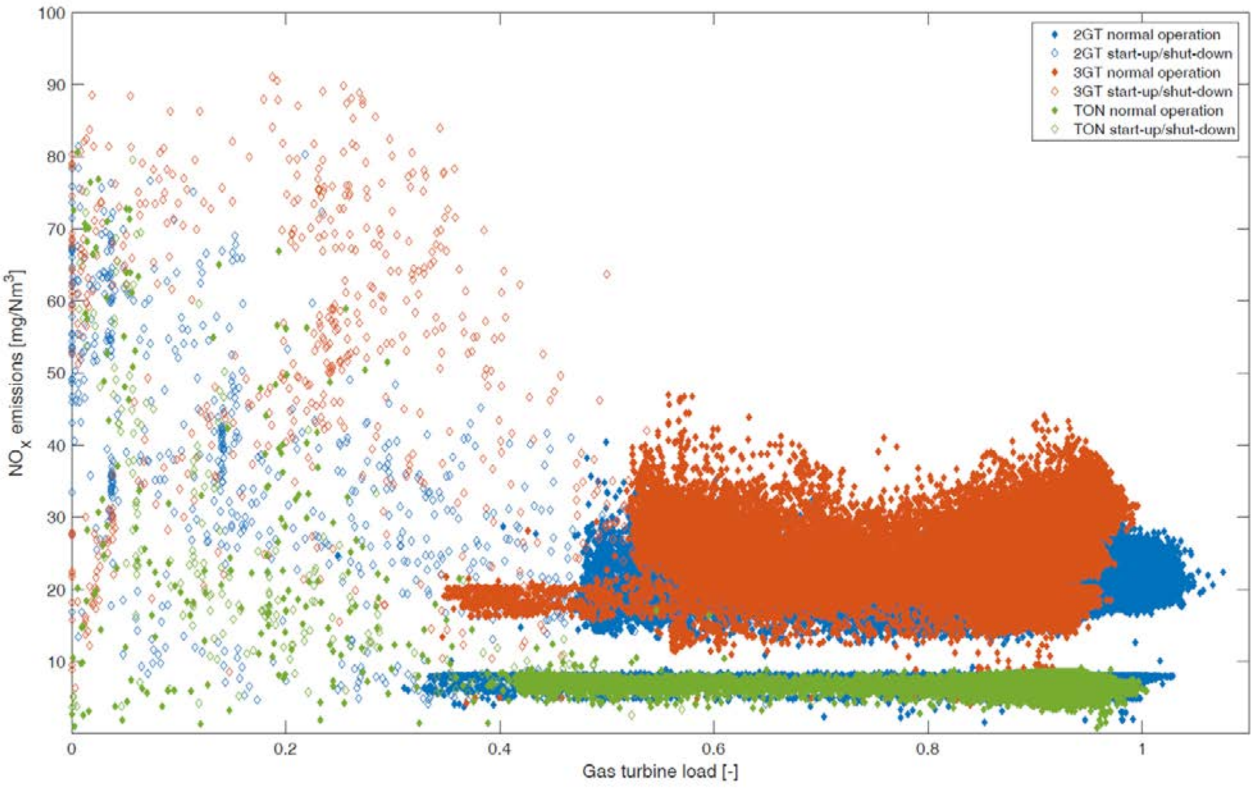

Figure 10 – Specific NO_X emissions for each unit w.r.t. gas turbine load.

Observing the behaviour of the 2GT unit, the difference between the first years, when no SCR was installed, and the last years (from the second semester of 2014) is clear. The installation of the SCR had a visible impact also on the 3GT unit, nevertheless its NO_X emission levels remain higher than the 2GT unit. The reason could be caused by some technical limitations, which caused the 3GT system to be smaller than the 2GT one; these limitations were certainly expected since the beginning of the plant operation, for which the legal limit has been fixed 3.5 times higher than the two other plants.

These variations are highlighted in Figure 11, where a chronological representation of the specific emissions is shown. While the decrease in 2GT is significant, the effect on 3GT appears less effective. In both units, the emissions remain lower than the limits that are applied to each system.

However, the use of a SCR cleaning system gives rise to NH_3 emissions, as ammonia is used in the process and a part of it is conveyed in the flue gases. These emissions are continuously monitored by the CEMS, and are significantly lower than the security limit, which is set by the national regulations to 5 mg/Nm^3 [20].

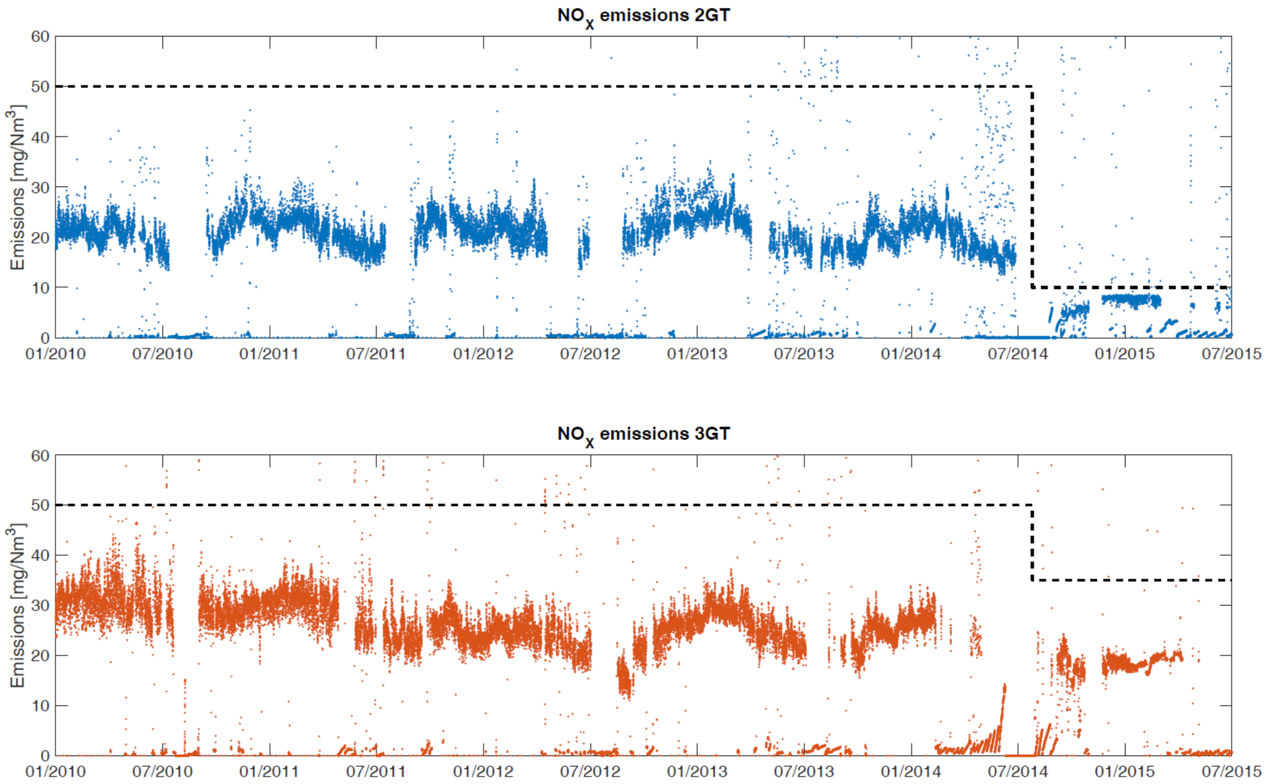

Figure 11 – Variation over time of specific NO_X emissions for Moncalieri 2GT and 3GT.

Conclusions

In this work, the real operation of three NGCC units has been analysed, considering the energy performance and the pollutants emissions over the years. The possibility of considering a wide dataset of hourly measurements has broadened the analysis over different operation conditions.

The energy operation of the NGCC units shows a good performance, with a large variability of the range of operation, considering the electricity production and the heat supplied to the DH system. The operation data confirm the high efficiency that can be reached by this technology. An analysis of the load profiles throughout the year shows that the units are operated with different strategies, depending on the heat required by the DH and the electricity market conditions. Performance curves of the gas turbines at partial load have been calculated by fitting the hourly actual operation performance.

Considering the pollutants emissions, the values are generally much lower than the limits set by the National regulations. The operation analysis allowed underlining the significant difference in NO_X emissions when installing a SCR gas cleaning system. The effectiveness of the SCR has been observed in two units by comparing the emissions before and after the SCR installation.

A significant criticality arises with CO emissions, which are significantly higher than in normal operation, up to three orders of magnitude, during plants' start-up and shut-down phases. This criticality has worsen in the last years, as the particular Italian market conditions forced this type of units to several start-up and shut-down procedures over the year, in order to operate as backup power following the non-programmable RES plants. This aspect should be taken into account when evaluating the benefits of a large share of RES sources in any electricity grid.

The operation analysis reported in this paper is part of a wider research activity, aimed at comparing the results obtained for the here studied units with those relative to other plants. The availability of operation data with high temporal details is crucial for these analyses; the presented analysis has shown that nominal values cannot be the only reference for effectively evaluating efficiencies and environmental performances of NGCC plants.

References

[1] EU, "The promotion of cogeneration based on a useful heat demand in the internal energy market".

[2] L. Holt and M. Galligan, "Energy Efficiency Policies as Part of Carbon Reduction Efforts: Lessons from the EU for the U.S.," *The Electricity Journal,* vol. 26, no. 7, pp. 33-42, 2013.

[3] G. Phylipsen, K. Blok and E. Worrell, Handbook on international comparisons of energy efficiency in the manufacturing industry, Utrecht University, 1998.

[4] R. Klaassen and M. Patel, "District heating in the Netherlands today: A techno-economic assessment for NGCC-CHP (Natural Gas Combined Cycle combined heat and power)," *Energy,* vol. 54, pp. 63-73, 2013.

[5] H. Lund, B. Möller, B. Mathiesen and A. Dyrelund, "The role of district heating in future renewable energy systems," *Energy,* vol. 35, pp. 1381-1390, 2010.

[6] NETL - DOE, "Current and Future Technologies for Natural Gas Combined Cycle (NGCC) Power Plants," June 2013. [Online]. Available: http://netl.doe.gov/File%20Library/Research/Energy%20Analysis/Publications/NGCC_SOA_ADV_Rev1_20130610.pdf. [Accessed August 2015].

[7] F. Gullì and A. Lo Balbo, "The impact of intermittently renewable energy on Italian wholesale electricity prices: Additional benefits or additional costs?," *Energy Policy,* vol. 83, pp. 123-137, 2015.

[8] J. Zapata Riveros, K. Bruninx, K. Poncelet and W. D'haeseleer, “Bidding strategies for virtual power plants considering CHPs and intermittent renewables,” *Energy Conversion and Management,* vol. 103, pp. 408-418, 2015.

[9] European Union, “The 2020 climate and energy package,” [Online]. Available: http://ec.europa.eu/clima/policies/package/index_en.htm.

[10] Terna Rete Italia, “Rapporto Mensile sul Sistema Elettrico, Consuntivo Dicembre 2014 (in Italian),” [Online]. Available: http://www.terna.it/LinkClick.aspx?fileticket=xlb5XQtu648%3d&tabid=379&mid=3013. [Accessed August 2015].

[11] S. Clò, A. Cataldi and P. Zoppoli, “The merit-order effect in the Italian power market: The impact of solar and wind generation on national wholesale electricity prices,” *Energy Policy,* vol. 77, pp. 79-88, 2015.

[12] G. Casolino, G. Liuzzi and A. Losi, “Combined cycle unit commitment in a changing electricity market scenario,” *International Journal of Electrical Power & Energy Systems,* vol. 73, pp. 114-123, 2015.

[13] E. Thorin, H. Brand and C. Weber, “Long-term optimization of cogeneration systems in a competitive market environment,” *Applied Energy,* vol. 81, no. 2, pp. 152-169, 2005.

[14] IREN Energia, “Moncalieri Plant - 2nd GT,” [Online]. Available: http://www.irenenergia.it/ChiSiamo/Media/brochure/files/Moncalieri_2GT_UK.pdf. [Accessed August 2015].

[15] IREN Energia, “Moncalieri Plant - 3rd GT,” [Online]. Available: http://www.irenenergia.it/ChiSiamo/Media/brochure/files/Moncalieri_3GT_UK.pdf. [Accessed August 2015].

[16] IREN Energia, “Plant Torino Nord,” [Online]. Available: http://www.irenenergia.it/ChiSiamo/Media/brochure/files/Torino_Nord_UK.pdf. [Accessed August 2015].

[17] SNAM Rete Gas, [Online]. Available: www.snamretegas.it/. [Accessed August 2015].

[18] W. Graus and E. Worrell, “Methods for calculating CO2 intensity of power generation and consumption: a global perspective,” *Energy Policy,* vol. 39, no. 2, pp. 613-627, 2011.

[19] IREN Energia, “Centrale termoelettrica di cogenerazione di Moncalieri, Dichiarazione Ambientale, Anno 2014, 2° aggiornamento annuale (in Italian),” [Online]. Available: http://www.irenenergia.it/opencms/export/sites/Energia/File_Gallery/EMAS_Moncalieri.pdf. [Accessed August 2015].

[20] IREN Energia, “Centrale termoelettrica di cogenerazione Torino Nord, Dichiarazione Ambientale, 1° sem Anno 2014 (in Italian),” [Online]. Available: http://www.irenenergia.it/opencms/export/sites/Energia/File_Gallery/Dichiarazione_ambientale_Cle_Torino_Nord_1_sem_2014.pdf. [Accessed August 2015].