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ATMOSPHERIC IMPACT OF POWER PLANT STACK EMISSIONS

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Abstract: The atmospheric impact of stack emissions from a tri-generation power plant that will be installed in an urban area in the central Po valley are studied and compared to the impact of the existing plant (conventional boilers). Both the plants are supplied by methane gas. The atmospheric dispersion of the emissions is simulated both in the current and the future scenario, i.e. before and after tri-generation plant activation respectively. The plant is assumed as a continuous emission point source. The emission rates are set equal to the regulatory emission limits for the existing plant and to the emission limits certified by the tri-generation system manufacturerfor the future plant. The local meteorological, topographical and surface land cover datasets have been used. The simulation periods span over each one of the four seasons, using 2010 meteorological data, to test conditions both favourable and unfavourable to pollutant accumulation in the atmosphere; simulation withperiod spanning over the whole 2010 year are also performed (long-term). The dispersion of different air pollutants (NO_xmainly) is presented; the concentration fields obtained for the same period in the two different scenarios are compared. The aim of the simulation is to estimate the impact of emissions on air quality in the urban area close to the plant, in different weather conditions, in a region characterized by calm wind events. The tri-generation power plant impact on air quality (i.e. respect to the regulatory concentration limits for pollutants in atmosphere) results lower than the impact of the existing plant, even if the yearly total mass of pollutants emitted in atmosphere from the tri-generation power plant is higher than from the existing plant. The simulation is performed by the software package ARIA INDUSTRY, that is made up of the 3D lagrangian stochastic particle dispersion model SPRAY, the diagnostic meteorological model MINERVE and the turbulence model SURFPRO.

Key words: *tri-generation power plant, atmospheric pollution, dispersion model, SPRAY.*

INTRODUCTION

The cogeneration is the simultaneous generation in one process of several types of energy (heat, mechanical and electrical energy) by means of a suitable plant unit, able to operate in cogeneration. A tri-generation power plant associates the production of electricity and heat to an energy absorber, in order to provide a cooling system for buildings. A tri-generation power plant allows primary energy saving and reduction of energy supply costs, compared to a traditional system, therefore the European Commission promotes the use of cogeneration systems (2004/8/CE).

A first reduction of atmospheric emissions achieved by a tri-generation plant compared to a conventional plant is due to the self production of electric power, reducing its needs of electricity supply from the Italian Electric Energy Network (IEEN). Therefore the pollutant emissions (mainly NO_x, SO_x, PM_{10} and greenhouse gases) due to electricity generation with conventional systems within the IEEN are avoided. The effects of the reduction in greenhouse gas emission (CO_2) has a relevance on a global scale, whereas the reduction in NO_x, SO_x and PM_{10} does not improve the air quality in the surroundings of the tri-generation plant, but close to the electric energy production plant.

The estimate of the benefit on local air quality by shifting from a conventional plant to of a tri-generation plant has to be focused on the comparison of their stack emissions rates. Tri-generation plants use different type of devices compared to conventional plants, along with a different operating procedure.

In the case study presented in this work, a tri-generation power plant with four-stroke engine will be installed in the General Hospital of a northern Italy town (Modena, central Po valley), to replace an existing plant with conventional boilers. Both plants are supplied by methane gas. The engine features and the emission limits of the tri-generation plant certified by the manufacturer show that the total amount of NO_x, CO and PM yearly emitted in the atmosphere by the tri-generation plant may results higher than the total yearly emission from the existing plant (test year 2010). On the contrary, the different operating procedure of the two plants consists in a wide difference in daily fuel consumption: the tri-generation plant fuel consumption is fairly steady, while the consumption for the existing plant shows a wide seasonality, with a peak in winter. The present and future scenarios are studied by means of the simulation of the emission plume from the stack of the present and future plant. The simulation focused on winter NO_x concentration and involved year 2010 as a test period. The simulation is performed by the software package ARIA INDUSTRY, that is made up of the 3D lagrangian stochastic particle dispersion model SPRAY, the diagnostic meteorological model MINERVE and the turbulence model SURFPRO.

CASE STUDY

The new tri-generation plant will be installed at the GeneralHospital, within the city of Modena (northern Italy, central Po valley, elevation 34 m a.s.l.) in a densely populated urban area. Thistri-generation plant will be a Jenbacher JMS 620 GS-N.L, whose approved electrical power is 3349 kWe and thermal power 3098 kW, with an internal combustion four-stroke engine powered by methane gas. The regulatory limits for atmospheric emissions of internal combustion four-stroke engine are set by Italian law (D.L. 152/06); the limits,evaluated in the exhaust dry gas flow with 5% oxygen (O_2), are set as follows: NO_x (as NO_2) =500 mg/Nm^3, CO = 650 mg/ Nm^3, PM_{10}=130 mg/ Nm^3. The tri-generation plant manufacturer certifies the following emission rates:NO_x (as NO_2) $\leq$ 250 mg/Nm^3, CO $\leq$ 300 mg/ Nm^3, $PM_{10}\leq$30 mg/ Nm^3. The specific emission of CO_2 certified by the plant manufacturer is 510 g/kWhe. The tri-generation plant stack, at nominal operating conditions, will emit in the atmosphere a dry gas flow of 13 920 Nm^3/h with 11.2% oxygen (O_2) content. The annual hours of operation necessary to meet the needs of the GeneralHospital are 7 010 (3471in winter e 3539 in summer season). The self production of electric power from tri-generation is expected to almost fulfil the energy requirements of the GeneralHospital, cooling of buildings included; about 4 013 MWh/y ofelectric energy must still be requested to the IEEN.

The current Central Heating of the General Hospital provides power for heating, hot water and other services (i.e. medical and kitchen); it includes five generators (conventional boilers) supplied by methane gas, with a total nominal power of 20109 MW. The total annual energy requirements of the GeneralHospital is actually 16 924 MWh/y. The regulatory limits for emissions of methane supplied boiler with a nominal power lower than 50 MW are set in the exhaust dry gas flow with 3% oxygen (O_2) as follows (D.L. 152/06 and Local Administration for CO limits): NO_x (as NO_2) = 350 mg/Nm^3, SO_x = 35 mg/ Nm^3, PM10 = 5mg/ Nm^3, CO = 100 mg/ Nm^3. The emission factor of CO_2 for the existing plant is 55.91 tCO_2/TJ (2003/87/CE Emission Trading Project). The current total electric energy needs to yearly supply the Hospital, the Central Heating Unit and the building cooling is of 25 494 MWh/year. This electric energy is actually supplied from the IEEN.

ANNUAL FLUX OF ATMOPSHERIC EMISSIONS IN THE ACTUAL AND FUTURE SCENARIO

An estimate of the annual atmospheric emissions from the tri-generation plant has been produced using actual consumption data reported in the previous paragraph, and hereafter indicated as the “nominal”operating conditions, i.e.: dry gas flow of 13 920 Nm^3/hwith 11.2 % oxygen (O_2), 7010 total annual hours of activity, emission valuesin the exhaust dry gas flow with 5% oxygen (O_2) certified by the plant manufacturer: NO_x (as NO_2) = 250 mg/Nm^3, CO = 300 mg/ Nm^3, PM_{10} = 30 mg/ Nm^3,specific emission of CO_2 =510 g/kWhe,operational condition 95% of the approved electrical power.

The total mass of NO_x, CO, SO_x, PM_{10} and CO_2 actually emitted in one year by the existing Central Heating has been estimated from the annual fuel consumption of the year 2010, equal to 2997016 Nm^3, a fuel amount very similar to that of previous years: in fact,usually only three of the five boilers operatecontinuously. The exhausts flow rate from the current plant has been estimated assumingmass conservation, stechiometric conditionof combustion with 1% excess air,exhaust gas temperature 423.15Kand that the boilers operate at steady state. The NO_x, CO, SO_x and PM_{10} concentration in the emissions are set equal to regulatory limits, i.e. NO_x (as NO_2) = 350 mg/Nm^3, SO_x = 35 mg/ Nm^3, PM_{10} = 5mg/ Nm^3, CO = 100 mg/ Nm^3, in the exhaust dry gas flow with 3% oxygen (O_2), and the emission factor for CO_2 = 55.91 tCO_2/TJ. This operating mode is hereafter indicated as the “calculated” operating conditions of the current plant. The resulting annual mass fluxes for the two plants are reported in Table 1 :

Table 7. Total annual mass emission from tri-generation and actual plant

Pollutant	Tri-generation plant	Existing conventional boilers
	Annual atmospheric emissions (t/year)	
NO_X (as NO_2)	14.94	10.62
CO	17.93	3.03
SO_X		1.06
PM10	1.79	0.15
CO_2	11347	5 865

In the future scenario, about 4 013MWh/y ofelectric energy must still be supplied from the IEEN, while currently the total electric energy needs for the General Hospital is of 25494 MWh/y. In table 2 are presented the emissions caused by the production of electric energy supplied by the national network to the needs of the tri-generation and actual plants: these emissions have been estimated from the atmospheric emission inventory for electric energy production plants in Italy (ENEL, 2010) and equal to: CO_2= 422 (g/kWh$_{eq}$), NO_x= 0.237 (g/kWh$_{eq}$), SO_x = 0.228 (g/kWh$_{eq}$), PM_{10}= 0.012 (g/kWh$_{eq}$).

Table 2. Total annual emissions due to the production of electric energy supplied by the IEEN in the future and in the current scenario

Pollutant	Tri-generation plant	Existing plant
	(t/y)	
NO_X	0.95	6.04
SOx	0.91	5.81
PM10	0.05	0.31
CO_2	1 693	10 758

Table 2 shows the reduction in emissions from electric energy production switching from the existing plant to a tri-generation plant (avoided emissions), although this reduction would affect the surroundings of the electric power plants. On the contrary, the direct atmospheric emissions rate from the tri-generation plant is higher than the current one: otherwise, for a correct impact assessment, also the operating mode of the two plants needs to be taken into account.

The local impact on air quality have been therefore evaluated by means of the simulation of the atmospheric dispersion of the pollutant plume emitted from the stack of the tri-generation and of the current plant, in the most critical operating condition for both plants and under both favourable and unfavourable meteorological conditions to pollutant dispersion.

SIMULATION BY MEANS OF THE DISPERSION MODEL SPRAY, STUDIED DOMAINS AND DATA SET

The simulation is performed by the software package ARIA INDUSTRY, that is composed of three main models: the dispersion model SPRAY, the diagnostic meteorological model MINERVE (Geai, 1987; ARIA Tech., 2001) and the turbulence model SURFPRO (Arianet, 2007a). SPRAY (Arianet, 2007b; Tinarelli et al., 1998) is a 3D Lagrangian stochastic particle dispersion model able to simulate air pollution dispersion and deposition-decay phenomena in non homogenous, non stationary conditions and over complex topography (Thomson, 1987). SPRAY supplies a 3D concentration field subdivided into grid cells vertically structured into terrain-following layers separated using a logarithmic progression.

The studied area is centered at the emission source, that is the location of the current and future power plant, close to the General Hospital of Modena. The spatial domain for diagnostic wind field estimation covers an area of 40 kmx40 km. The domain origin (South-West corner) is located at cartographic coordinates 634 106 m East and 4 924 131 m North (UTM-WGS84). The domain is divided into a horizontal grid of 500 m square cells, and into a vertical grid of 30 layers from the ground to 1800 m. For the computation of pollutants concentration fields, the domain is limited to an area of 20 km x 20 km, centered at the emission source, divided into a grid of 250 m square cells: in this inner and smaller domain, the source results located at the 9.80 km (X) and 9.95 km (Y) respect the new SW corner. The emission source is simulated as a continuous point source.

The simulations are performed using hourly meteorological data acquired by Osservatorio Geofisico of the University of Modena and Reggio Emilia (Modena, Italy) and byRegional Environmental Agency (ARPA) ground stations and meteorological data simulated by CALMET model (ARPA). Ground elevation datacomes from DEM dataobtained from the Shuttle Radar Topography Mission (SRTM), sampled at 3 arc-seconds, whileland use – land surface cover dataset is extracted from the European CORINE Land Cover 2000 dataset (European Environment Agency) in raster format with a spatial resolution of 100 m x 100 m.

Source data and features are shown in table 3: the current plant is composed of 3 boilers, very close to each other, whose total emissions are simulated as a single point source; the exhaust speed in the flow from the current boiler stacks has been indirectly estimated from the stack diameters and the exhaust gas flow, calculated as reported in the previous paragraph. The dataof the tri-generation future planthas been collected from the design technical report of the plant.

Table 3. Source data of current and of future tri-generation plant

	stack	X (m)	Y (m)	stack height (m)	stack diameter (m)	gas temp (K)	gas speed (m/s)
current	1	9 800	9 950	12	0.44	423.15	3.22
current	2	9 800	9 950	12	0.44	423.15	3.22
current	3	9 800	9 950	12	0.38	423.15	3.70
future	1	9 800	9 950	10	0.70	398.15	15.00

Atmospheric dispersion of the emission plume has been simulated under most critical operating conditions for both plants. Since the tri-generation plant is expected to operate at steady state under the “nominal” conditions previously reported, these same steady state is assumed valid also during most critical conditions. The “nominal”operating conditions of the tri-generation plant involve that the emissions will be about constant throughout the year and then the strength of the impact on air quality will be mainly affected by the occurring meteorological conditions.

The current plant is assumed to operate at the “calculated” conditions, and the simulation of emission plume dispersion is performed using the daily fuel consumption of year 2010. The 2010 record of daily fuel consumption shows a very high variability, ranging from 22 143 Nm^3 (peak consumption in December) to 2 067 Nm^3 (minimum consumption in July). Consequently, a high variability results in the daily exhausts emission rate from the current plant stacks and, finally, in the daily mass of pollutants emitted in atmosphere. The simulation has been performed assuming the pollutant emission rates for the current plant equal to the regulatory emission limits. The impact on air quality in the current scenario is determined by the combined effect of the emission trend and of the concurrent meteorological conditions.

Firstly, the simulation of the dispersion of the pollution plume is performed during winter, both in the current and future scenario. The year 2010 is assumed as test year, therefore year 2010 meteorological data have been used for the simulation both in the current and in the future scenario. Simulation time step has been set to one hour, due to the hourly meteorological input data. Simulations were performed for all pollutants subjected to regulatory limits (see previous paragraph), and focused on NO_x, being the most critical for methane fuelled plant. Moreover NO_x concentration in urban areas, in case of intense vehicular traffic emissions may be close or higher than regulatory limit. Besides, in the urban area of Modena, NO_x hourly average concentration results one of the most critical pollutant among those emitted by the investigated stack. Therefore only NO_x concentration maps are reported and discussed in this study.

Figure 1 shows the maps of average simulated NO_x ground concentration in winter 2010 obtained by SPRAY simulation; figure 1 illustrates the wide difference between the two plant operating conditions. To represent the maximum impact case, the tri-generation plant is assumed to operate stationary at its “nominal” conditions, while the current plant is assumed to operate at the “calculated” condition, at the maximum daily fuel consumption for year 2010 (22 143 Nm^3/d), corresponding to the highest emission flow. However, this fuel consumption is not uncommonly high in winter, since the average daily fuel consumption in December 2010 is 17 468 Nm^3 (st. dev. 12.7%) and the monthly consumption is similar throughout the winter season (the standard deviation ofmonthly fuel consumption in January, February, March and December 2010 is 10%).
The simulated plumes, both in the current and the future scenario (respectively pane left and right in Figure 1) are stretched along the mainwind direction (approximately from to North-West to South-East). The 2010 winter season was characterized by meteorological conditions adverse to pollutant dispersion, due to a frequency of low wind events (i.e. wind speed < 2 m/s)equal to 74%. Moreover maximum daily mixing heightin winter 2010 ranged between 250 – 600 m, reaching 800 m in late February. These meteorological conditions, favorable to pollutant accumulation in the atmosphere,characterized the central part of the Po valleyin autumn and winter and have been enhanced by the flat topography of the area. Air quality limits for NO_x (maximum hourly concentration 200 $\mu g/Nm^3$, 2008/50/CE and DL 156/2009) has been compared to the simulated concentration and represented in the concentration maps (Figure 1): the variability of the impact on air quality

determined by the plant emissions is clearly shown by this comparison. In the current scenario, the average NO_x concentration values in winter ranges from 0.35 to about 15 μg/Nm^3, while in the future scenario the highest concentration values are lower than 1.6 μg/Nm^3. In case the simulation would be performed assuming the average winter daily fuel consumption value for the current plant (14 578 Nm^3) instead of the maximum, atmospheric NO_x concentration would be ~20% lower, however higher than the tri-generation values. Moreover, contour lines in Figure 1 indicate a lower concentration gradient for the tri-generation plant compared to the current plant.

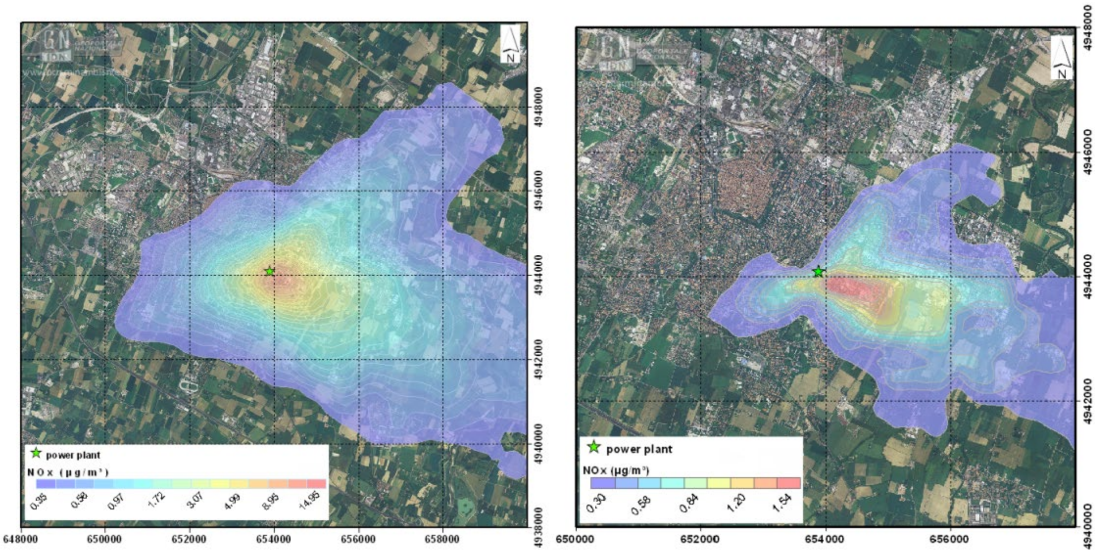

Figure 1. NO_x concentration plumes at ground from the current Central Heating plant of the main hospital of Modena (left), and from the tri-generation plant (right), simulated by SPRAY. Simulation period ranges from January 1st to March 20th 2010. The plant stack location is the same both in the current and in the future scenario (the center point of the domain).

The average of maximum NO_x hourly concentration from all winter simulations has been calculated and resulted in 12.46 μg/Nm^3 and 69.14 μg/Nm^3 for the tri-generation and current plant respectively.

The average value of the concentration maxima results clearly higher for the current plant, resulting the 34.5 % of the regulatory limits, while for the tri-generation plant represents the 6.2 % of the regulatory limits.

These results indicate that, in winter season, the atmospheric NO_x concentration in Modena may be significantly affected by the current plant emissions. In fact, if weather conditions favorable to pollutant accumulation occur, the current plant emission may locally lead to concentration values closer to the regulatory limits; on the contrary, the impact of the tri-generation plant, even during adverse meteorological condition, should be always far from these limits. The NO_x average atmospheric concentrations measured by local environmental agency in urban sites in Modena (Table 4) is characterized by the heavy vehicular traffic and clearly show the impact of current plant emissions on local air quality.

Table 4. NO_Xseasonal average atmospheric concentrations measured by local Environmental Agency (ARPA) in urban sites in Modena

Pollutant	Winter (μg/Nm^3)	Spring (μg/Nm^3)	Summer (μg/Nm^3)	Autumn (μg/Nm^3)
NO_x	80.55	54.84	42.54	57.48

In seasons other than winter, the fuel consumption from the current plant is lower than in winter, leading to a lower impact on air quality: the maximum decrease in stack emission impact occurs in summer, due tothe lowest fuel consumption and the high atmospheric mixing enhancing pollutant dispersion in the atmosphere. A comparison among the seasonal simulations shows NO_x concentration at ground decreasing from the winter values, reported in Figure 1, to summer values lower than 1 μg/Nm^3.

The emission flow from the tri-generation plant is expected to be quite steady throughout the year. The annual average NO_x concentration map for the emissions from the tri-generation plant, when operating at "nominal" conditions, is presented in Figure 2. The yearly mean concentration values do not differ strongly from the winter mean and thehighest concentration values are lower than 1.6μg/Nm^3. The emissions of the tri-generation plant, although in late spring and summer are higher than the current plant emissions, will not impact significantly local air quality, due to the better atmospheric mixing during the warmer season.

Since SPRAY does not simulate,in this case study,pollutant deposition and reaction phenomena, asimulation of the dispersion of other pollutants subjected to regulatory limits (e.g. SO_x, PM_{10}, CO), will be highly similar to NO_x concentration maps: concentration maps for SO_x, PM_{10} or CO, over the same time interval, would result in a scale of NO_x maps, starting from SO_x, PM_{10} and COconcentration in the emissions.

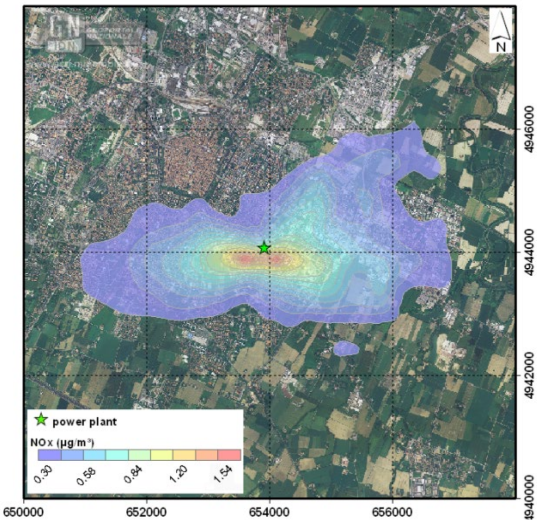

Figure 2. Annual average (year 2010) NO_x concentration plumes at ground from the tri-generation plant, simulated by SPRAY. The plant stack location is in the center point of the domain.

CONCLUSIONS

The atmospheric impact of stack emissions from the tri-generation power plant that will be installed in the urban area of the city of Modena(central Po valley, Italy), to supply the city hospital, was compared to the impact of the existing plant (conventional boilers).The self production of electric energy by the tri-generation plant enables to avoid the emissions due to the electric energy generation, although this reduction in emission will not affect local air quality, but the area surrounding electric power plants of the national network. The annual stack emission in the atmosphere, evaluated as total mass flux of pollutants, results higher for the tri-generation plant than for the current plant. A simulation of pollutant dispersion from the stack of the plant has been performed by SPRAY dispersion model, both in the current and future scenario. Dispersion focused on NO_x, for the criticality of its concentration level in urban areas proved the influence of the different operating mode of the two plants in affecting local air quality. The current plant emissions have a strong seasonality and in winter they may lead to NO_x local concentration close to the regulatory limits. The emissions from the tri-generation plant will be fairly steady throughout the year, resulting lower than current plant emission in winter and early autumn, buthigher in late spring and summer season. In spite of this, the simulation shows that the emissions from the tri-generation plant do not influence significantly local air quality in any season of the year, because of the its steady operating condition.

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