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# IMPACT ASSESSMENT OF POLLUTANT EMISSIONS IN THE ATMOSPHERE FROM A POWER PLANT OVER A COMPLEX TERRAIN

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**Abstract**: The development of a natural gas-fired tri-generation power plant (520 MW Combined Cycle Gas Turbines (CCGT) + 58 MW) in the Republic of San Marino (RSM), a small independent country in Northern Italy, is under assessment. The power plant has the aim to meet completely the energy requirements of RSM and export part of its production to Italy. The present work investigates the impact assessment of pollutants emitted in the atmosphere from the power plant stacks, subjected to the regulatory limits defined by the Italian law (DL 152/2006 and DL 46/2014, implementation of 2010/75/EU). The impact assessment was performed via lagrangian simulation of the atmospheric dispersion of the emitted plume by the means of the Aria Industry package (Aria Technologies, France, and Arianet, Italy).The RSM is almost completely mountainous, 10 km West of the Adriatic Sea coast and then affected by a land-sea breeze circulation: SPRAY resulted a suitable modeling suite due to its ability to simulate atmospheric pollution dispersion under both non-homogenous and non-stationary conditions and over a complex topography. The emission scenario was simulated both during a worst-case meteorological condition and during 10-days periods representative for each season. The plant was assumed in continuous operation throughout the day. The dispersion was simulated for $NO_x$ and CO pollutants. The simulated concentrations were compared with the air quality limits of the Italian law (DL 155/2010 implementation of 169 2008/50/EC). Since the simulated concentration of CO were widely lower than the regulatory limits, the simulation focused only on $NO_x$. In spite of the very high pollutant emission rate from the plant stacks, the simulation showed a limited environmental impact: average hourly concentration at ground level were very low, with only isolated peaks where the emitted plume hits the mountain reliefs. The most critical values were detected by the simulation on the hillside of the Mount Titano (749 m a.s.l., the highest peak in RSM), close (4 km West), and downwind, to the future power plant.

***Key words:*** *SPRAY, tri-generation power plant emission, atmospheric dispersion, $NO_x$, CO, complex topography.*

## INTRODUCTION

The European Commission (EC) promotes and supports the reduction in energy consumption, the increase in energy efficiency, the increase in energy production from renewable sources and the reduction in greenhouse gas (GHG) emissions; these commitments were set out in the Directive 2009/29/EC and commonly called European 20-20-20 targets. One of the preliminary action promoted by EC to fulfill the Directive purposes is the promotion of the cogeneration (Directive 2004/8/EC), combined heat and power (CHP) production in a single process. Electricity production technologies are coupled with heat recovery equipment (Dharmadhikari 1997; Chicco and Mancarella, 2006; Khaliq, 2008), producing simultaneously and sustainably heat and electricity. The CHP self-production of electric power reduces the needs of electricity supply from the electric energy network respect to conventional boilers, therefore pollutant (mainly $NO_x$, $SO_x$ and $PM_{10}$) and GHG emissions due to conventional electricity generation are avoided. For these reasons, environmental politicies support the diffusion of cogeneration plants.

Nevertheless, the atmospheric impact of pollutants emitted from cogeneration plant must be assessed in comparison with the air quality regulatory limits: the air pollution caused by plant emissions receive more attention by the population, affecting directly the human health.

That impact depends upon the plant emission performance and on the dispersion of its stack emissions in atmosphere, i.e. also the meteorological conditions and the local landscape features may be relevant.

The atmospheric impact assessment of the stack emissions of power plants is one of the main applications of air quality atmospheric dispersion models. The Directive 96/62/CE and Italian law (DL 351/99) allow the application of dispersion models. The Directive 2008/50/EC and Italian law (DL 155/2010) view various model features and set the uncertainty which may be applied to a simulated concentration model

result. The simulation of pollutant dispersion by different models may produce not comparable results in some specific atmospheric conditions, such as low winds (Brusasca et al., 2001) or local scale winds of breeze, and also over complex topography (Nanni et al., 1996; Gariazzo et al., 2004; Pession et al., 2005).
The development of a natural gas-fired tri-generation power plant (520 MW Combined Cycle Gas Turbines (CCGT) + 58 MW) in the Republic of San Marino (RSM), a small independent enclave placed in Northern Italy, is under evaluation. The power plant will completely fulfill the energy needs of RSM and be able to support energetically the neighboring Italy.

The present work investigates the provisional impact assessment of atmospheric emissions from that cogeneration plant stacks, in the framework of the Italian law regulatory limits (DL 152/2006 and DL 46/2014). The impact assessment was performed via Lagrangian simulation of the atmospheric dispersion of the exhaust gases emitted from the cogeneration plant stacks, by means of the package Aria Industry (Aria Technologies, France, and Arianet, Italy). The RSM is an almost completely mountainous territory, placed about 10 km from the Adriatic Sea coast and then affected by local scale winds of land-see breeze, overlapped to a synoptic circulation. The study includes simulation results of the power plant during a worst-case scenario and three periods well representative of low, moderate and large atmospheric dispersion conditions respectively. Only $NO_x$ and CO were simulated, being the two compounds having regulatory emissions limit for this power plant. Finally, the impact of atmospheric emissions on local air quality and on exceedance of air quality regulatory limits is discussed (DL 155/2010).

## THE COGENERATION PLANT

The cogeneration plant is the Mitsubishi MHPS GT Model M701F5 and H-25(42) Combined Cycle Gas Turbines (CCGT, 520MW and 58MW thermal power) powered by methane gas. The features of the plant and the estimates of $NO_x$ concentrations in the dry exhaust gas (based on 15 % $O_2$) for both the CCGT plant units are reported in Table 1 (Manufacturer, personal communication).
Regulatory emission limits are set by the Italian law for combustion plants with nominal thermal power > 50MW, large combustion plants (DL 152 3/04/2006 and DL 46 4/03/2014, implementation of Directive 2010/75/UE). Regulatory limits for new power plants Gas Turbines (CCGT included) supplied by methane gas are equal to 30 mg/Nm$^3$ for $NO_x$ and 100 mg/Nm$^3$ for CO in dry exhaust gas (based on 15% $O_2$). However, for plants with efficiency > 35%, the law (DL 46/2014) sets the emission limit for $NO_x$ equal to 30 × η (35%), where η (%) is the efficiency of the plant. For the plant in project, whose efficiency η = 61% (as assured by the Manufacturer), the $NO_x$ emission limit results in 52 mg/Nm$^3$.

**Table 1**. Power Plant features

| Source unit | Stack height | Stack inner diameter | Exhaust gas flow | Exhaust gas temperature | Gas exit velocity | $NO_x$ |
|---|---|---|---|---|---|---|
| | (m) | (m) | (Nm$^3$ h$^{-1}$) | (°C) | (m s$^{-1}$) | (mg Nm$^{-3}$) |
| **M701F5 CCGT** | 70 | 6.2 | 1 885 000 | 85 | 25 | 50 |
| **H-25(42) CCGT** | 70 | 2.7 | 290 000 | 85 | 20 | 50 |

## SOFTWARE, DATA SET AND INVESTIGATION DOMAIN

The simulation of the dispersion of the pollutant emitted by the plant was performed by the software package ARIA INDUSTRY which includes the dispersion model SPRAY, the diagnostic wind field meteorological model SWIFT and the turbulence model SURFPRO. SPRAY is a Lagrangian stochastic model for the simulation of the dispersion of passive pollutants in a complex terrain and non-homogenous conditions, under calm and low wind events (Ghermandi et al., 2012) and gives highly reliable simulations of pollutant dispersion close to the release source point (Ghermandi et al., 2014); enhancement of SPRAY code at micro scale are used for urban applications (Ghermandi et al., 2015).
SPRAY supplies a three-dimensional concentration field, vertically subdivided into grid cells at different terrain-following layers, and vertically stretched to obtain higher resolution near the ground. The thickness of the first layer is set to 10 m, starting from the ground level. The diagnostic wind, temperature and concentration fields were computed over the spatial domain of 40 x 40 km$^2$ divided into a horizontal grid of 200 m square cells and into a vertical grid of 10 layers from the ground to 1500 m above ground level. The pollutants concentration fields were computed also over a spatial domain of 20 x 20 km$^2$, divided into a horizontal grid of 100 m square cells. The studied domain is always centered at the

location of power plant stacks. Each single stack is simulated as an independent emitting source. The emission sources of the power plant were simulated as nonstop continuous release source points.

The year 2014 was chosen as reference period. Measured meteorological data from 16 ground-based stations of the Italian Environmental Agency network surrounding the power plant site in RSM, and simulated input data (vertical wind profile close to the source point) provided by the mesoscale COSMO atmospheric model (LAMA dataset), were used as input data for the meteorological model.The wind rose for the year 2014 at the meteorological ground station closest to the source shows a wind climate in the site driven by mesoscale circulation, mainly characterized by moderate winds blowing from North West – West and, with lower frequency, from North East – East.

Ground elevation data were provided by the Shuttle Radar Topography Mission through United States Geological Service (USGS), while the land use/land cover (LULC) dataset was extracted by the European CORINE Land Cover (CLC) 2012 inventory.

The RSM is an enclave in Italy, on the border between the regions of Emilia Romagna, and Marche, at about 10 km from the Adriatic Sea coast and covers an area of about 61.2 $km^2$ almost completely mountainous (83 % of its territory); the highest point in the country is the summit of Mount Titano (749 m a.s.l.). The RSM is affected by land-see breeze superimposed to the mesoscale circulation. The power plant will be installed (Fig. 1) close to the Italian border, at an elevation of about 120 m a.s.l.

The simulations were performed considering both a period favorable to air pollution buildup (worst-case scenario) and three periods representative of typical meteorological conditions for the season under investigation, for the year 2014. The air pollution network of Italian Environmental Agency showed that the period between $11^{th}$ and $20^{th}$ March 2014 was highly critical for air quality in the neighboring regions of Emilia Romagna and Marche, because the intense anthropogenic emissions of winter season were combined with meteorological conditions unfavorable to pollutant disperson in atmosphere (60% wind calms). Therefore that period was chosen as a worst-case. Two periods in June 2014 were considered as representative of the summer season: June $6^{th}$ to June $15^{th}$ and June $19^{th}$ to June $28^{th}$. Low PBL depth occurred in the former, and high PBL depth and intense wind speed in the latter respectively. The fall period from November $8^{th}$ to $17^{th}$ was characterized by low PBL depth and low wind, with about 28% of calm events. In this fall period the effect of local sea-breeze circulation was not negligible, but it was less evident than in the March and summer periods.

**RESULTS AND DISCUSSION**

For each period of analysis, the simulations were performed with an hourly time-step according to the hourly meteorological input data. The plant was considered under steady-state operation (specific features in Table 1). In dry exhaust gas (based on 15 % $O_2$ ), the emitted $NO_x$ concentration was set to 50 mg $Nm^{-3}$, as provided by the Manufacturer, and slightly below the emission limit of 52 mg $Nm^{-3}$, and CO concentration was assumed equal to the regulatory limits (100 mg $Nm^{-3}$ ).

This conservative approach is suitable to investigate the potential role of stack emissions in the exceedance of air quality regulatory limits (D.Lgs. 155 13/08/2010, implementation of 169 2008/50/EC): 200 $\mu g\ m^{-3}$ for hourly $NO_2$ (not to be exceeded more than 18 times per year), 40 $\mu g\ m^{-3}$ for annual $NO_2$ mean concentration and 10 mg $m^{-3}$ for CO maximum daily eight hour mean concentration.

The simulated concentrations were compared with the air quality limits; since the simulated CO ground concentrations resulted always largely lower than the regulatory limits, they were omitted.

The simulation results for the most critical period, from March $11^{th}$ to $20^{th}$, 2014 are shown in Figure 1 as map of average hourly $NO_x$ concentrations from the plume emitted by the power plant, in the first atmospheric layer (10 m) mapped over the Digital Terrain Model (DTM) of the spatial domain (20 x 20 $km^2$, at left, and 40 x 40 km $km^2$, at right. The maps in Figure 1 and all further analysis include only simulated ground concentrations higher than 1 $\mu g\ m^{-3}$ (plume concentrations).

The simulated plume appears stretched approximately from West to East. The average hourly $NO_x$ concentration maximum value in the investigated period is 65 $\mu g\ m^{-3}$, at about 5 km West from the power plant, close to the Mount Titano relief, that represents a physical barrier to the plume dispersion. The plume concentration at ground over the domain is lower than 2 $\mu g\ m^{-3}$. On the larger domain (40 x 40 $km^2$), isolated concentration with maximum values of about 90 $\mu g\ m^{-3}$ occur against natural obstacles (as hills), about 25 km South - East of the plant.

The effect of local sea-breeze was investigated on March $14^{th}$, 2014, as the most representative day. The maximum average hourly $NO_x$ ground concentration for March $14^{th}$, 2014, was 110 µg/m³ and occurred close to the Mount Titano, due to the local sea-breeze combination with the prevailing atmospheric circulation at mesoscale. The average plume value for the domain is equal to 2.2 µg/m³.

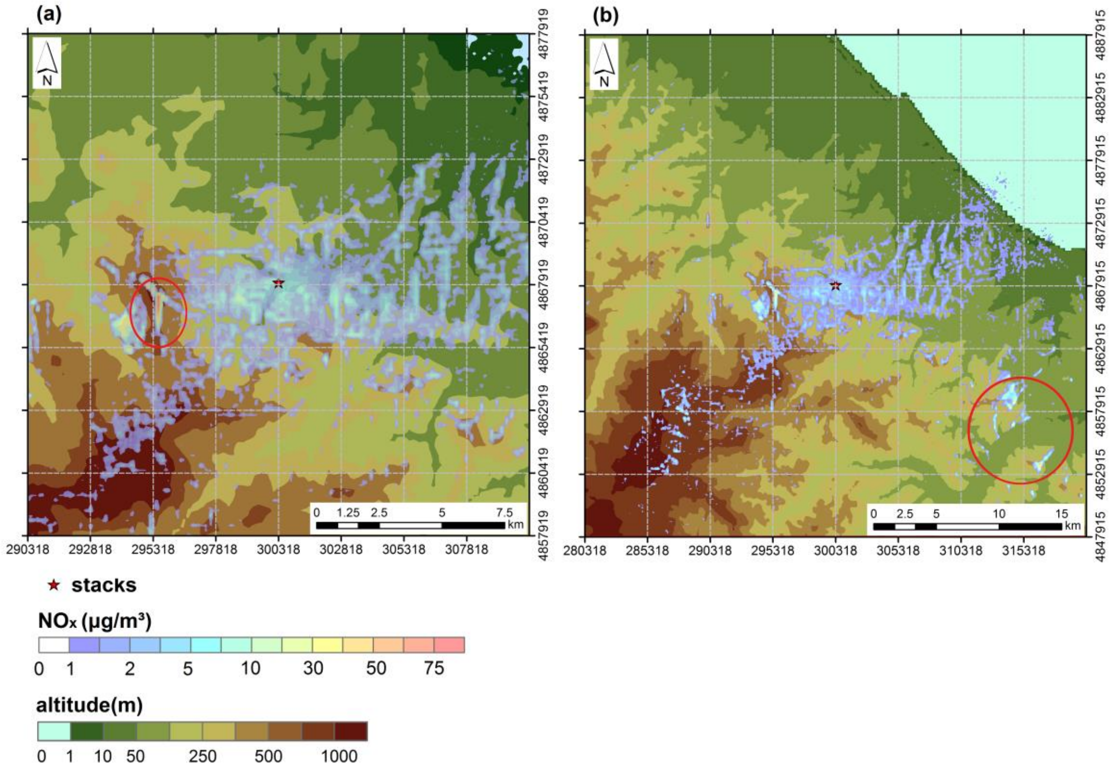


**Figure 1**: (a) Average hourly $NO_x$ ground concentration plume from the power plant, mapped over the DTM spatial domain of 20 x 20 km$^2$ and (b) of 40 x 40 km$^2$. The color scales refer to $NO_x$ concentration (top) and to altitude above m.s.l. (bottom). The simulation operates in terrain-following coordinates. The concentration maximum values are outlined with red circles The plant site is in the center of the domain (red star) – March 11$^{th}$ to 20$^{th}$, 2014.

The plume concentration at ground over the domain result lower than 2 µg m$^{-3}$also for the the summer and fall period simulations. In the first summer period from June 6$^{th}$ to 15$^{th}$, 2014, a maximum of 77 µg m$^{-3}$, is obtained close to Mount Titano, while in the second summer period from June 19$^{th}$ to 28$^{th}$ , 2014, the Western winds are the most intense, the plume is mainly dispersed toward the Adriatic Sea with maximum of almost 30 µg m$^{-3}$, occurring at 15-18 km East South-East of the power plant; concentrations of about 12 µg m$^{-3}$ are obtained on the slope of Mount Titano relief. In the fall period (from November 8$^{th}$ to 17$^{th}$, 2014) the Northwest - West winds are the most intense dispersing the plume toward the mountain relieves to the Southeast side of the source, with a local maximum of almost 390 µg m$^{-3}$, occurring 15 km Southeast of the power plant. Values of about 29 µg m$^{-3}$ result close to Mount Titano.

The $NO_x$ pollutant roses for the four simulation periods performed using SWIFT wind data for the source point at the plant stack elevation and the hourly $NO_x$ ground simulated concentrations in a 100 m x 700 m area over the Eastern slope of Mount Titano, where recurrent concentration peaks are expected, were used to obtain conditional bivariate probability functions (CBPF) (Uria-Tellaetxe and Carslaw, 2014). Each CBPF estimates the probability that a specific concentration range is observed within a given wind sector, depending upon wind speed. CBPF showing the probability frequency of $NO_x$ concentration higher than the hourly regulatory limit for each wind speed and direction classes has been outlined. The concentration range used to compute CBPF considered levels larger than the regulatory limit of 200 µg m$^{-3}$, corresponding to the 94.2$^{th}$ quantile for the critical period of March, 2014, to the 94.8$^{th}$ for November, to the 98.5$^{th}$ from June 19$^{th}$ to 28$^{th}$ , and to 99.2$^{th}$ quantile from June 6$^{th}$ to 15$^{th}$ representative periods. The outcome of CBPF were compared to wind roses for each investigated period, that show the percentage of wind conditions that may be responsible of concentration peaks around the Mount Titano area: the exceedances of regulatory limits occur in presence of wind

events blowing from Northeast - East and of wind calms. The frequency of the wind events blowing from Northeast - East in the year 2014, from the 2014 wind rose at the meteorological ground station closest to the plant, is of about 11% while the calms correspond to 7.0% in the year.
Therefore, the regulatory limit for average hourly $NO_x$ concentration is expected to be exceeded more than 18 times a calendar year, but limited to the focus area on the Eastern slope of Mount Titano: in the nearby domain cells, $NO_x$ concentration sharply decreases to values largely lower than the regulatory limits.

## CONCLUSIONS

The investigation shows that the regulatory limit for average hourly $NO_x$ concentration is already exceeded more than 18 times during the investigated periods, but limited to a wide, steep slope area along the cliff of Mount Titano. The power plant emissions will be expected to meet the pollution limit for air quality for $NO_x$ average hourly concentration (200 μg $m^{-3}$ ), throughout the investigated domain, except around the area close to Mount Titano relief. Due to its location respect to the source, this area may be considered the most exposed to a local accumulation of pollutants emitted from the power plant. Yet, it is fortunately not a residential area due to its steep morphology.
Similarly, the power plant emissions will be expected to meet the pollution limit for air quality for $NO_x$ annual mean average (40 μg $m^{-3}$) throughout the investigated domain, except around the area close to Mount Titano relief. Single peaks (in scattered domain cells) mainly occur in different areas of the domain for each simulated period, without the evidence of recurring accumulation points. CO ground concentrations resulted always largely lower than the regulatory limits.
The paper highlighted the SPRAY ability in reliably simulating the dispersion of a pollution plume through a complex terrain and under unsteady wind conditions.

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