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Assessment of Geothermal Power Plants Impact on Air Quality – Effect of H_2S Abatement with AMIS® in the Larderello-Travale-Radicondoli Geothermal Area (Tuscany).

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ABSTRACT

This study is a regional assessment of the results achieved by the installation of AMIS® abatement systems on geothermal power plants in reducing the potential impact associated with emissions of hydrogen sulfide (H_2S) and mercury (Hg) in the Larderello-Travale-Radicondoli Geothermal Area (Tuscany).

The AMIS® abatement system has "rated values" of efficiency up to 90% for H_2S and 95% for Hg. Starting from the year 2002, AMIS® abatement systems have been installed on new and existing geothermal power plants progressively in the frame of a program still in progress.

This study evaluated the effects of the AMIS® spread in the geothermal concession comparing the scenario for the year 2003 (27 power plants, 1 with AMIS® for a total installed capacity of about 720 MW) with the 2007 scenario (27 power plants, 10 with AMIS® for a total installed capacity of about 720 MW).

The study was conducted both analyzing the air quality measured and by applying the CALMET-CALPUFF modelling system.

The results show that in the 2007 scenario the reduction of the GPPs contribution to the annual average concentration of H_2S is greater than 25% in 90% of the domain and greater than 40% in about 10% of the domain. The reduction in the number of odour threshold exceedances induced by the power plants (not considering the natural background concentration) is greater than 10% in the 90% of the domain and greater than 50% in about 10% of the domain.

1. INTRODUCTION

1.1 The Traditional Area

The Larderello-Travale-Radicondoli Geothermal Area, known as the Traditional Area, is located in southern Tuscany (Provinces of Siena, Grosseto and Pisa) on the peri-Tyrrhenian margin of the Italian peninsula. The Traditional Area and the Amiata Area are the two tuscan geothermal areas suitable for the exploitation of geothermal resources for power generation. These areas represent two of the six most important vapor-dominated geothermal fields in the world for the production of electricity (the others are The Geysers, in California, Kamojang and Darajat in Indonesia and Matsuwaka in Japan).

In 2010 32 geothermal electric power plants were operating in Tuscany, for a total installed capacity of 772 MW and a gross production of 5'375,9 GWh, equal to 26,5% of the Tuscany Region needs (ARPAT, 2011) and 1,8% of the National needs (Ministero Sviluppo Economico, 2011).

The heat source of the geothermal reservoir in the Traditional Area is a granitic batholith intruded at shallow depth into the terrestrial crust due to the orogenic movements that led to the Apennines formation. The generated geothermal reservoir is a vapour-dominated field, in which the physical state of the fluid is dry-saturated or superheated steam. Only about 10% of the geothermal fields in the world are vapour-dominated (the remaining fields are hot water-dominated or pressurized water-dominated, in which the fluid is present is in the liquid state with a certain amount of steam), but they produce almost half of electricity from geothermal sources. In vapour-dominated fields the steam pressure is greater than 1 atm, with a temperature higher than 200°C and, consequently, high enthalpy (2800 Kj/kg). The steam is suitable to be transformed directly into mechanical energy in the turbine allowing a higher electrical conversion efficiency respect those of the water-dominated fields.

The industrial cultivation of geothermal fields for the power production in the Traditional Area had a boost in the mid-1960s, and it experienced a significant development in the '90s. The emissions in the atmosphere associated to geothermal electric power plants grew simultaneously to their development, incrementing the pre-existing level produced by the numerous natural phenomena such as hot springs, mud pots and fumaroles.

1.2 The geothermal electric power plant (GPP)

Due to the favorable steam characteristics (high enthalpy, low non-condensable gas content), the geothermal power plants (GPP) in the Traditional Area are Dry Steam plants. The steam travels directly to a turbine, which drives a generator that produces electricity. The non-condensable fraction of the fluid, averaging 4% by weight of the extracted fluid, makes this technology particularly efficient, also thanks to the use of centrifugal compressors for maintaining the vacuum in the condensers. The specific steam consumption of these Dry steam plants is typically ranging from 6 to 8 kg/kWh, depending on the field pressure. After the expansion in the turbine, the endogenous fluid is condensed in a direct-contact condenser and cooled in an evaporative cooling tower. A fraction of the extracted geothermal fluid, resulting from the difference between the amount of water obtained by the steam condensation and the amount of water that evaporates from the cooling towers, is sent to the re-injection wells, preventing hydrological imbalances and prolonging the duration of the geothermal reservoir.

The cooling tower is the point source of the emission in atmosphere from the GPP. There gather the two flows that contribute to the overall release: the non-condensable gases and the "drift" (liquid aerosol), entrained by tower air flow.

The non-condensable gases (NCGs) flow contains the substances originally present in the geothermal fluid in the physical state of gas (carbon dioxide, methane, hydrogen sulphide, nitrogen, argon, oxygen and hydrogen) and the other substances, such as mercury, which are, under the condenser operating conditions, in vapor phase. Therefore, the NCGs flow constitutes the most part of the climate-altering substances, hydrogen sulphide, and mercury vapor emission. This flow contains also small amounts of ammonia and arsenic vapor.

The outcoming "cooling tower" gas flow is generated by the countercurrent passage of the cooling air through the condensed fluid, dispersed in drops by appropriate diffusion systems. There, the contact with the air flow causes both a partial evaporation of the circulating liquid (reducing the drops volume) and a mechanical stripping, a drag out of the smaller droplets with the cooling air. During this process a part of the substances contained in the condensed fluid passes in the air (including ammonia and a small quantity of hydrogen sulphide and mercury), joining the non-condensable gases flow, before being emitted from the tower. This is the process responsible of the drift (aerosol) and of gas phase emission.

1.3 The AMIS® abatement system

Since the mid-1990s Enel started a research program for the development of an abatement systems for Hydrogen Sulfide and Mercury (known by the Italian acronym AMIS® "Abbattimento Mercurio e Idrogeno Solforato"), which are the major critical pollutants emitted by geothermal power plants.

The first AMIS® pilot plant was built in the late 1990 at the Piancastagnaio 4 GPP allowing for the testing of materials and the development of engineering solutions. The first AMIS® industrial prototype was built in 2000 at the Bagnore 3 GPP. The installation of AMIS® systems continued with the progress of years. A total number of 16 AMIS® systems were operating at the end of 2008, serving 19 geothermal power plants. The installation plan carried out by Enel in the subsequent years was such that 28 of the 34 units in operation were equipped with AMIS® as of the end of 2012 (24 out of 30 in the traditional area).

AMIS® is a proprietary technology that, if the natural alkalinity of the condensate fluid is adequate, doesn't require the use of chemicals. It doesn't produce sulphur based by-products to be landfilled or recycled. As (Baldacci A., 2005) has stated, the AMIS® treats the NCGs and is located before the entrance to the cooling towers. The process is constituted by three fundamental steps:

- mercury removal by chemical absorption;
- selective catalytic oxidation of H_2S to SO_2;
- SO_2 scrubbing by geothermal water.

Elemental mercury is removed from NCG flow by chemical absorption on a fixed bed of sorbent (selenium mass or sulphured activated carbon). Before entering mercury absorber, the process gas is cooled and subsequently compressed in order to achieve the optimal pressure, temperature (about 70°C) and relative humidity conditions for the reaction. Gas compression provides the hydraulic head required to compensate the pressure drop of the AMIS® system.

The selective catalytic oxidation of hydrogen sulphide (H_2S) to sulphur dioxide (SO_2) is the second basic step of the process. NCG are heated up to the minimum temperature required by the catalyst to promote oxidation according to the reaction:

$$H_2S + 3/2\ O_2 \Rightarrow SO_2 + H_2O \qquad [1]$$

The reaction is exothermic. The enthalpy of the hot stream leaving the catalytic reactor is recovered to preheat the cold stream leaving mercury absorber. The process is completely regenerative, so that no external heating is required during normal operation. Some air is added to the gaseous stream to be treated in order to provide the oxygen needed for H_2S oxidation and catalyst temperature control.

The final step of the process is the absorption of the produced SO_2 by geothermal water. In most cases, geothermal fluids contain basic soluble compounds, especially ammonia, so that these are naturally present in the geothermal water. Basic compounds allow the absorption of acidic components, such as sulphur dioxide (SO_2). The efficiency of SO_2 absorption essentially depends on the molar ratio between produced SO_2 and ammonia in the geothermal water. If geothermal water contains enough ammonia, SO_2 removal is close to 100% without addition of any chemical. Otherwise it is possible to achieve the same result by adding ammonia water, thereby increasing the natural ammonia content of the geothermal water, or, as an alternative, sodium hydroxide (NaOH). The reaction products of SO_2 scrubbing are soluble (sulphites, thiosulphites and thiosulphates). The water leaving the absorption column re-enters the cycle of the geothermal water, controlled by the cooling tower overflow.

The Tuscany Environmental Protection Agency (ARPAT Dipartimento di Siena, 2011) report a mean measured efficiency values, referred to the NCG flow, equal to 98 ÷ 99% for hydrogen sulphide and 93 ÷ 94% for mercury. Since, as before-mentioned, the AMIS® treats exclusively the NGC flow, i.e. the gases extracted from the mixing-condenser by the compressors, the efficiency values are slightly lower if referring to the overall emission from the cooling tower. It is necessary, in fact, to consider the H_2S and Hg stripped by the air in the cooling tower that is not treated by AMIS®, which therefore constitutes the residual emission of hydrogen sulphide and mercury in AMIS®-equipped GPP.

Although further studies on methods for the measurement of cooling towers emissions are in progress, ARPAT (ARPAT, 2011) report an average global efficiency values, referred to the total emission of the GPP, equal to 82-85% for hydrogen sulphide and 50-60% for mercury.

The AMIS® outputs are:

- The condensed geothermal fluid, re-injected into the geothermal reservoir;
- The treated gases emitted into the atmosphere via the cooling tower.

1.4 Emissions evolution from 2003 to 2007

This study considers the situation of the Traditional Area in the years 2003 and 2007. In both years there were 27 operating GPPs, with a nominal power of about 720 MW. Only Travale 3 e Travale 4 Power Plants were equipped with AMIS® in 2003, while in 2007 the AMIS-equipped GPPs were 10.

The following Table 1 shows the total annual emissions in the Traditional Area in 2003 and 2007 (Regione Toscana, 2010) for hydrogen sulphide and mercury. Thanks to the installation of 9 AMIS® systems the total emissions significantly decreased (-26% for H_2S and -19% for Hg) despite an increase in production of 6%. The average specific emissions of H_2S per MWh produced decreased over the five years of 30%, from 4,20 kg/MWh to 2,93 kg/MWh. The average specific emissions of Hg per MWh produced decreased of 23% in five years, from 0,21 g/MWh to 0,16 g/MWh.

Figures 1 and 2, and Figures 3 and 4, for H_2S and Hg respectively, show the location of the GPP emissions in the two years considered. The dot sizes are proportional to the annual emission of each GPP.

Table 1: Power Production, emissions and emission factors in the Traditional Area.

Traditional Area	2003	2007	% var.
Annual Production [GWh]	4’413	4’675	6%
H_2S annual emission [Mg]	18’554	13’690	-26%
Hg annual emission [kg]	905	734	-19%
H_2S emission factor [kg/MWh]	4,20	2,93	-30%
Hg emission factor [g/MWh]	0,21	0,16	-23%

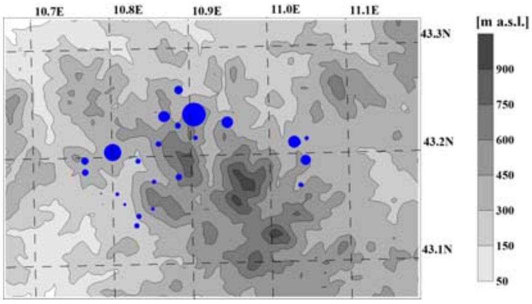

Figure 1: H2S Emission spatial distribution, year 2003.

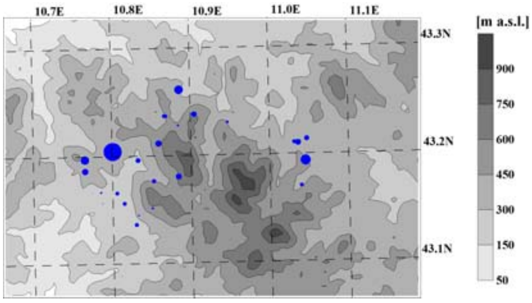

Figure 2: H_2S Emission spatial distribution, year 2007.

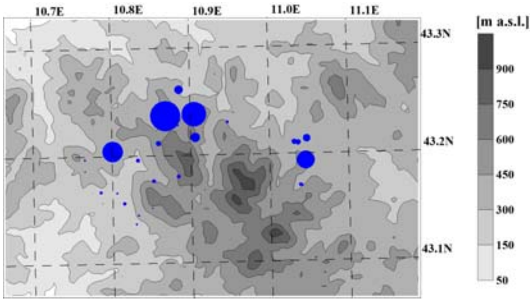

Figure 3: Hg Emission spatial distribution, year 2003.

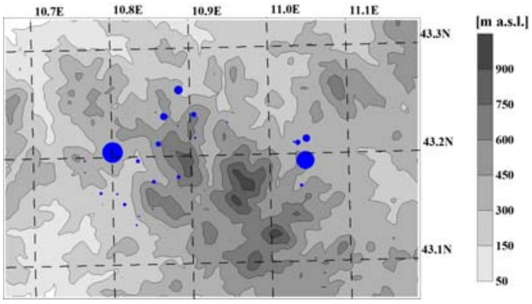

Figure 4: Hg Emission spatial distribution, year 2007.

1.5 Air quality reference values

The emission of H_2S and Hg are considered the main potential impacts of the GPPs.

Hydrogen sulphide is a colorless gas with a characteristic foul odor. It is a precursor of the secondary inorganic aerosol. It is oxidized in the air at a relatively slow rate by molecular oxygen, but at a much faster rate by OH^-. The atmospheric residence time is typically of 2-3 days in relatively clean air. It is slightly soluble in water and acts as a weak acid, giving the hydrosulphide ion HS^-. H_2S occurs in volcanic gases, natural gas, and some well waters. It also results from the bacterial anaerobic digestion of organic matter in the absence of oxygen, such as in swamps and sewers. In geothermal areas the concentration levels in ambient air could be significantly affected by emissions from natural sources.

Mercury is emitted by GPPs both in gaseous and in particulate form. Reactive gaseous mercury is both substantially more soluble in water and more reactive than elemental mercury. It remains in the atmosphere from one to ten days, and therefore tends to be deposited locally and regionally - from a few kilometers to a few hundred kilometers from its source. Its limited range of travel, solubility, and high reactivity contribute to its ultimate presence in biota on a regional basis. Mercury particulate is mercury bound to the drift water droplets. It is mainly deposited locally (according to droplet size distribution). However, it is less available to living organisms than the reactive gaseous form.

The European and Italian legislation does not define limit values, alert thresholds and/or target values for hydrogen sulphide and mercury. In the absence of normative references it is a standard practice, both at national and international level, to consider the guidelines set by the World Health Organization (WHO, 2000). ARPAT, in collaboration with other Tuscan public bodies, identified the following "criteria and reference values" for the protection of human health for H_2S and Hg (Regione Toscana, 2010): 150 H_2S $\mu g/m^3$ as 24-hrs average (WHO, 2000); 100 H_2S $\mu g/m^3$ as 1-14 days average (WHO, 2003); 20 H_2S $\mu g/m^3$ up to 90 days average (WHO, 2003); 200 Hg ng/m^3 as annual mean (U.S. Dep. of Health and Human Services, ATSDR, 1999). H_2S and Hg air concentrations detected by the monitoring activities of Enel and ARPAT (ARPAT Dipartimento di Siena, 2011) are significantly lower than the reference values, allowing excluding concerns for the human health. Thus, the main criticality is the odor annoyances related to the unpleasant odor of hydrogen sulphide. In the following, the effect of AMIS® installation is evaluated in terms of annual average concentration (for H_2S and Hg) and odor annoyances frequency expressed as exceedances of the threshold hydrogen sulphide concentration proposed by WHO (WHO, 2000), and adopted by ARPAT, in order to avoid substantial complaints among the exposed population, that should not exceed 7 $\mu g/m^3$, with a 30-minute averaging period.

1.6 Air quality monitoring in the Traditional Area

The air quality in the Traditional Area is monitored by the Enel Air Quality Monitoring Network, established between 1995 and 2002. The network consists of 11 hydrogen sulphide monitoring stations and 4 meteorological stations located in the major population centers. In addition, air quality monitoring is conducted also by ARPAT by means of mobile laboratories, to conduct periodic monitoring campaigns, and one monitoring station. In the framework of a voluntary agreement between Enel and Regione Toscana, an on-going project aims to achieve the acquisition of Enel Monitoring Network data by ARPAT.

Figure 5 shows the location of Enel meteorological and air quality monitoring stations.

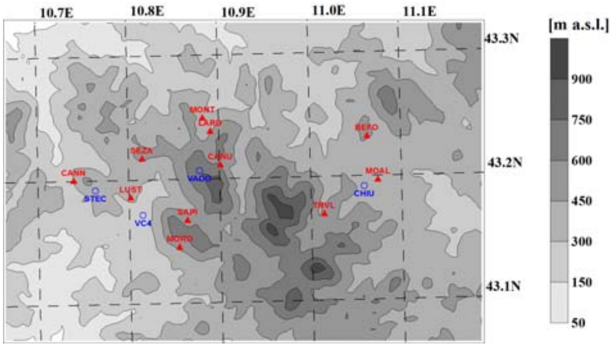

Figure 5: Meteorological Ground Stations (circles) and Air Quality Monitoring Stations (triangles).

2. OBSERVED AIR QUALITY IMPROVEMENT

Table 1 shows the statistics calculated on Enel Monitoring Network observations. It should be considered that values for Montecerboli station (MONT) have a representativeness of a few meters from the instrument position. Until April 2012, when the station has been repositioned, the instruments were in fact highly influenced by the emissions from a very close district heating network.

Figure 6 and Figure 7 show the scatter diagrams for each monitoring station of H_2S concentrations measured in 2003 versus those of 2007. The figures refer respectively to the annual mean concentration and to the annual percentage of hours with odor annoyance.

Table 1: H_2S observed in 2003 and 2007.

	2003			2007		
H_2S Monit. Station	Data avail. [%]	Mean conc. [μg/m^3] 1)	Exc. [%] 2)	Data avail. [%]	Mean conc. [μg/m^3] 1)	Exc. [%] 2)
BEFO	94	8.3	42	99	6.8	39
CANN	96	10.8	44	94	6.6	45
CANU	78	25.0	80	99	11.1	63
LARD	95	17.4	57	99	10.1	55
LUST	89	16.4	67	91	20.4	66
MOAL	96	12.1	53	98	5.4	52
MONT 3)	95	34.3	65	88	24.1	70
MORO	99	12.0	52	96	9.7	53
SAPI	98	12.7	52	99	13.3	51
SEZA	99	13.1	50	94	7.3	53
TRVL	83	6.6	30	94	5.4	27

1) Annual mean H_2S concentration observed [μg/m^3]
2) Exceedance hours of 7 H_2S μg/m^3 threshold [%]
3) Affected by emissions from a CHP

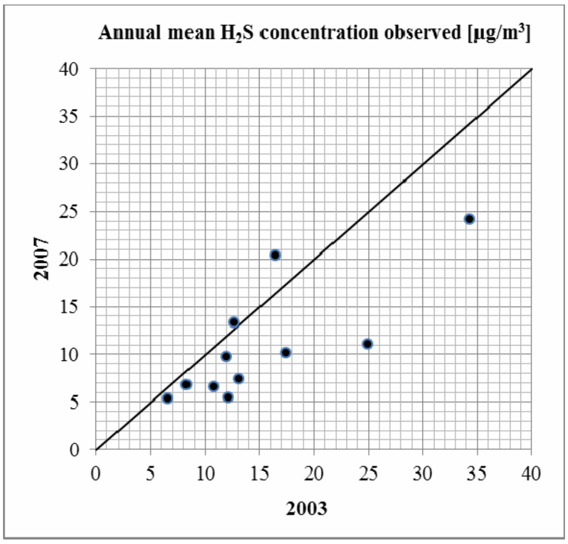

Figure 6: 2003 vs. 2007 annual mean H_2S concentration observed.

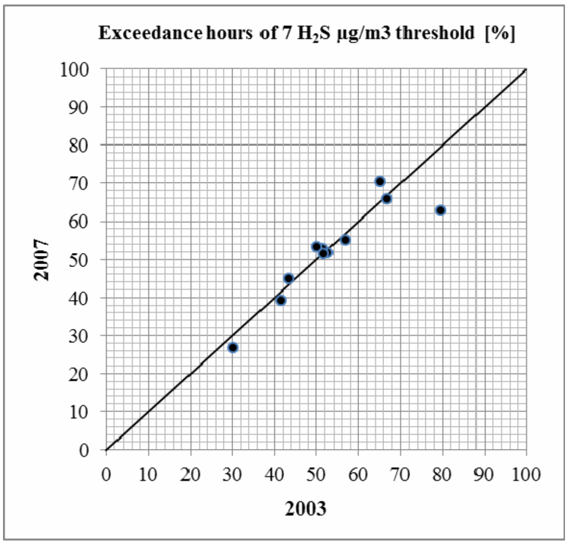

Figure 7: 2003 vs. 2007 number of odor annoyance hours H_2S concentration observed.

The figures show an overall improvement in air quality both in term of annual average and odor annoyance frequency. As shown in Table 2, the reduction is greater for long term concentration with reduction achieved in all the stations with the only exception of Lustignano (LUST) and Sasso Pisano (SAPI). The average reduction is -27% but some station registered a much greater values (up to -56%). The reduction in term of odor annoyances is less, generally equal to few percentage point (-3% on average). This fact could be addressed to the extremely low threshold value and to the presence of natural emissions that create a background concentration in the Traditional Area that could be greater than the threshold itself.

Table 2: Observed H_2S reduction (2007 vs. 2003).

Monitoring Station	Annual mean [μg/m^3]	Exc. Hours [%]
BEFO	-18%	-6%
CANN	-39%	3%
CANU	-56%	-21%
LARD	-42%	-3%
LUST	24%	-2%
MOAL	-56%	-2%
MONT	-30%	8%
MORO	-19%	3%
SAPI	5%	-1%
SEZA	-44%	6%
TRVL	-19%	-12%

3. AMIS® CONTRIBUTION TO AIR QUALITY IMPROVEMENT

The reduction calculated from the observed data, does not reflects only the effects of AMIS® installation but the result is also influenced by meteorological condition variability and variations in anthropogenic and natural emission sources other respect the GPPs.

To discriminate the contribution due to the installation of AMIS® abatement systems an air quality modeling exercise has been performed. Air quality modeling is a technique used to calculate concentrations of pollutants through the simulation of atmospheric physics.

The CALMET/CALPUFF modeling system (Scire J.S. et al., 2000) has been applied for the meteorological year 2007 considering two emission scenarios:

- The 2003 configuration: 27 GPPs, 1 with AMIS, total installed capacity of about 720 MW;
- The 2007 configuration: 27 GPPs, 10 with AMIS, total installed capacity of about 720 MW.

The modeling exercise allowed estimating the reduction of H_2S and Hg due to the installation of AMIS® systems, eliminating the influence of meteorological condition variability and variations in anthropogenic and natural emission sources other respect the GPPs.

The CALMET/CALPUFF modeling system has been applied on a domain of 43x29 km^2, with a spatial resolution of 0,5x0,5 km^2, characterized by a complex terrain and anemology. 8 vertical layers defined the vertical grid definition with cell face heights equal to 0, 20, 40, 80, 160, 400, 800, 1500, 3000 m agl.

CALMET/CALPUFF is an advanced non-steady-state meteorological and air quality modeling system developed and distributed by Earth Tech Inc. (Scire J.S. et al., 2000). The model has been adopted by the U.S. Environmental Protection Agency in its Guideline on Air Quality Models (U.S. EPA, 2005) as the preferred model for assessing long range transport of pollutants and on a case-by-case basis for certain near-field applications involving complex meteorological conditions. The modeling system consists of three main components and a set of preprocessing and post processing programs. The main components of the modeling system are CALMET (a diagnostic 3-dimensional meteorological model), CALPUFF (an air quality dispersion model), and CALPOST (a post processing package).

The CALMET diagnostic meteorological model generates three-dimensional, hourly or sub-hourly, gridded fields of meteorological parameters (such as air temperature, wind, relative humidity, precipitation) and two-dimensional micrometeorological variables (such as stability class, mixing height, friction velocity, Monin-Obukhov Length…) accounting for observations of meteorological variables and effects caused by terrain and surface characteristics. The CALMET model can provide four-dimensional data assimilation pairing observed data from surface observation stations, upper air (radiosonde) observation stations, and precipitation observation stations, with data from prognostic mesoscale meteorological models such as the MM5, NCEP, WRF, ETA, or RAMS. In general, CALMET utilizes two steps to develop a final wind field. First, the prognostic wind field is introduced into CALMET as the initial guess field. Once the initial guess field is created, CALMET adjusts the data by accounting for the kinematic terrain effects, slope flows, blocking effects, and three-dimensional divergence minimization. The wind field resulting from this step is called the Step 1 wind field. Then CALMET further adjusts the Step 1 wind field by applying an objective analysis procedure with observational data from selected surface, upper air, and precipitation stations. This step generates the final wind field (Step 2 wind field).

In this study CALMET (Version: 6.327, Level: 090511) used wind fields produced by WRF with a grid resolution of 3.5 km as initial guess field. The observed data from the 4 meteorological ground stations of Enel Monitoring Network were introduced in CALMET objective analysis procedure. In the modeling domain there are a significant portion of remote areas and local topographic features, such as valleys and canyons, without any locally observed meteorological data. Pseudo surface meteorological data were created from WRF surface layer to supplement available observational data to adequately represent local meteorological patterns. In other words, WRF generated meteorological fields to drive CALMET run at finer resolutions in order to resolve the effects of the finer scale terrain on the meteorological fields and thus resolve meteorological structures forced by the terrain, such as terrain channeling, wind-blocking, and gravity driven slope flows. As Robe F.R. et al. (1998) and Klausmann A.M. et Al. (2003) stated, improvements in meteorological fields are achievable by blending prognostic simulations with diagnostic meteorological model.

The CALPUFF model is a lagrangian puff model in which individual puffs of pollutant are released and are allowed to grow in the horizontal and vertical directions using the distribution coefficients in the Gaussian plume model in which pollutants spread outward from the centerline of the plume following a normal statistical distribution. The lagrangian puff dispersion formulation treats plumes as a series of Gaussian puffs that move and disperse according to local conditions that vary in time and space.

CALPUFF (Version: 6.268 Level: 100308) was used for the dispersion modelling of the emissions in atmosphere form the 27 GPP cooling towers. A total number of 92 point sources were defined to consider multiple-cell towers. To consider maintenance shutdown and breakdown the simulation has considered an AMIS® annual availability factor of 90%. Therefore, the emission rates for AMIS® equipped GPP have been computed using a weighted average of the values with and without the abatement system. Moreover, the engine rooms, the cooling towers and any other buildings have been considered in order to take into account the building downwash effect for each GPP.

3.1 GPPs contributions at monitoring stations

Table 3 shows the statistics calculated at Enel Monitoring Station locations extracted from the CALPUFF output. Figure 8 and Figure 9 show the scatter diagrams for each monitoring station of H_2S concentrations computed for 2003 emission scenario versus those of 2007. The figures refer to the GPP contribution to the air quality respectively in terms of annual mean concentration and annual percentage of hours with odor annoyance.

As reported also in Table 4, the figures show an overall improvement in air quality both in term of annual average and odor annoyance frequency. The results confirm those achieved from the observed data analysis; reduction is greater for long term concentration with reduction achieved in all the stations. The average reduction is -32% but some station registered a much greater values (up to -43%).

The reduction in term of odor annoyances entirely induced by GPPs (not considering the natural background concentration and other sources contributions) is -23% on average, much greater than the observed (see Table 4 versus Table 2). This result seem to suggest that just a minor part of odor annoyances may be generated by GPPs and that a significant role is played in the Traditional Area by other emissions (both natural and anthropogenic).

Table 3: H_2S modeled for 2003 and 2007 GPPs emission scenarios.

	2003		2007	
H_2S Monit. Station	Mean conc. [µg/m^3] 1)	Exc. [%] 2)	Mean conc. [µg/m^3] 1)	Exc. [%] 2)
BEFO	5.8	13	3.8	12
CANN	2.2	19	1.5	16
CANU	8.0	31	5.0	24
LARD	5.8	32	3.5	24
LUST	7.2	19	5.2	16
MOAL	3.3	23	2.4	18
MONT	5.0	28	3.2	21
MORO	6.3	10	4.5	6
SAPI	7.0	28	5.2	21
SEZA	13.1	24	7.5	19
TRVL	4.5	39	3.5	29

1) Annual mean H_2S concentration observed [µg/m^3]
2) Exceedance hours of 7 H_2S µg/m^3 threshold [%]

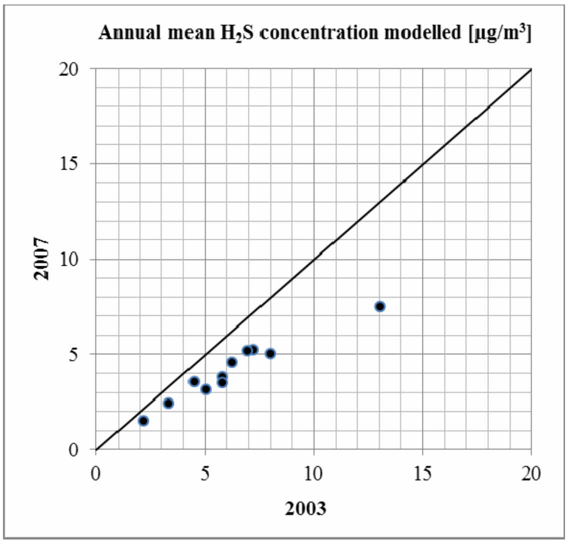

Figure 8: 2003 vs 2007 annual mean H_2S concentration modeled (GPPs contribution).

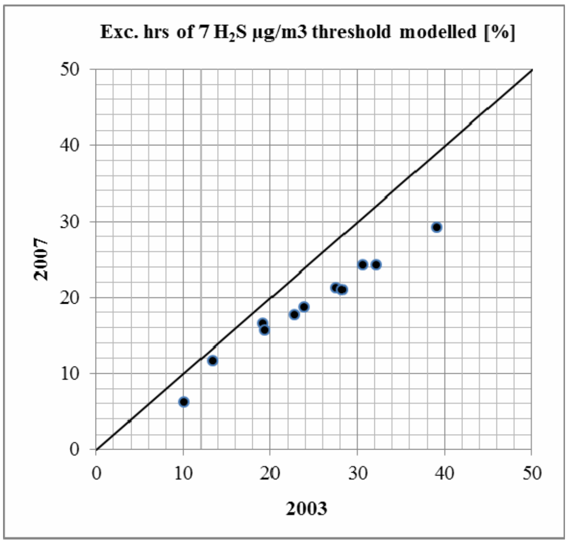

Figure 9: 2003 vs. 2007 number of odor annoyance hours H_2S concentration modeled (GPPs contribution).

Table 4: Modeled H_2S reduction (2007 vs. 2003) (GPPs contribution).

Monitoring Station	Annual mean [µg/m^3]	% Exc. Hours
BEFO	-35%	-13%
CANN	-32%	-15%
CANU	-37%	-21%
LARD	-40%	-25%
LUST	-28%	-19%
MOAL	-28%	-22%
MONT	-37%	-23%
MORO	-28%	-39%
SAPI	-26%	-25%
SEZA	-43%	-22%
TRVL	-21%	-26%

3.2 H_2S and Hg maps

The following figure 10 shows the mean annual H_2S ground concentration average estimated by CALPUFF. The concentration constitutes the impacts on air quality of the geothermal power plants. The upper figure “a)” is referred to the 2003 emission scenario, the “b) is referred to the 2007 emission scenario, the lower figure “c)” shows the percentage variation. The reduction is estimated greater than 25% in 90% of the domain, greater than 30% in about 55% of the domain and greater than 40% in about 10% of the domain.

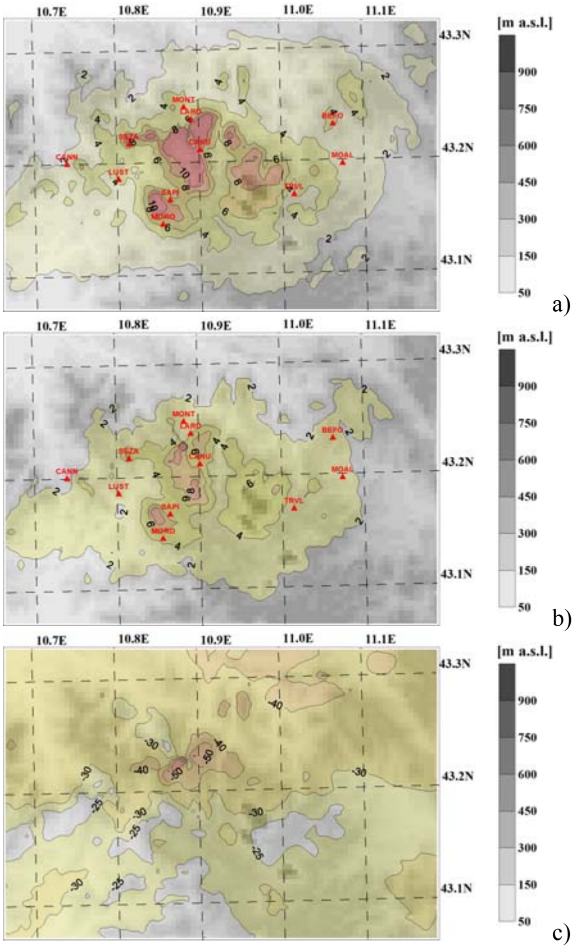

Figure 10: H_2S annual mean concentration [μg/m^3] from GPPS: 2003 emission scenario; b) 2007 emission scenario; c) % variation.

Figure 11 shows the same information for the mean annual concentration of mercury. The reduction estimated is greater than 30% in 90% of the domain, greater than 37% in about 50% of the domain and greater than 50% in about 10% of the domain.

The analysis of odor annoyances entirely induced by GPPs (not considering the natural background concentration and other sources contributions) is reported Figure 12. The reduction estimated is greater than 10% in 90% of the domain, greater than 30% in about 50% of the domain and greater than 50% in about 10% of the domain. Has to be noted the greater percentage reductions are estimated in the boundaries of the domain (where the exceedances occur rarely).

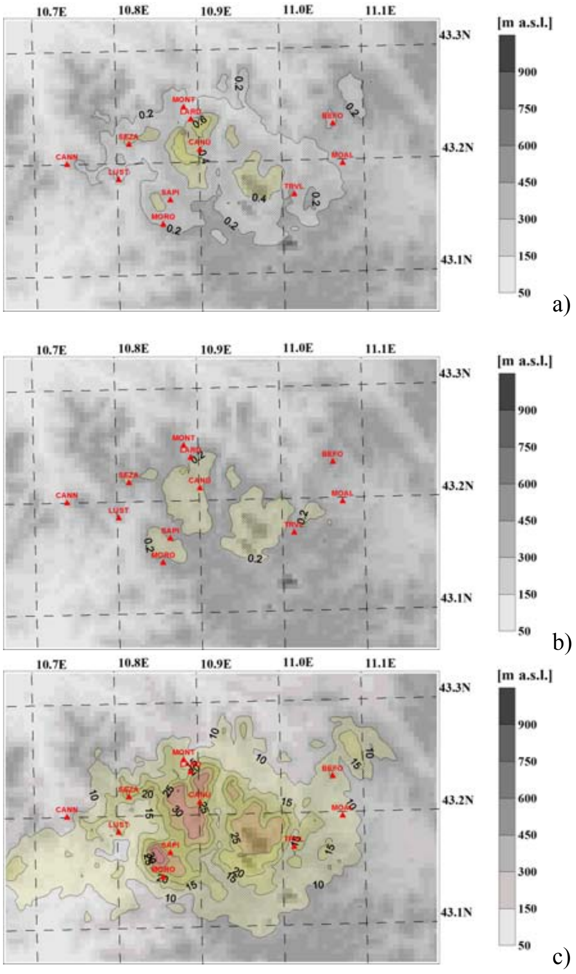

Figure 11: Hg annual mean concentration [ng/m^3] from GPPS: 2003 emission scenario; b) 2007 emission scenario; c) % variation.

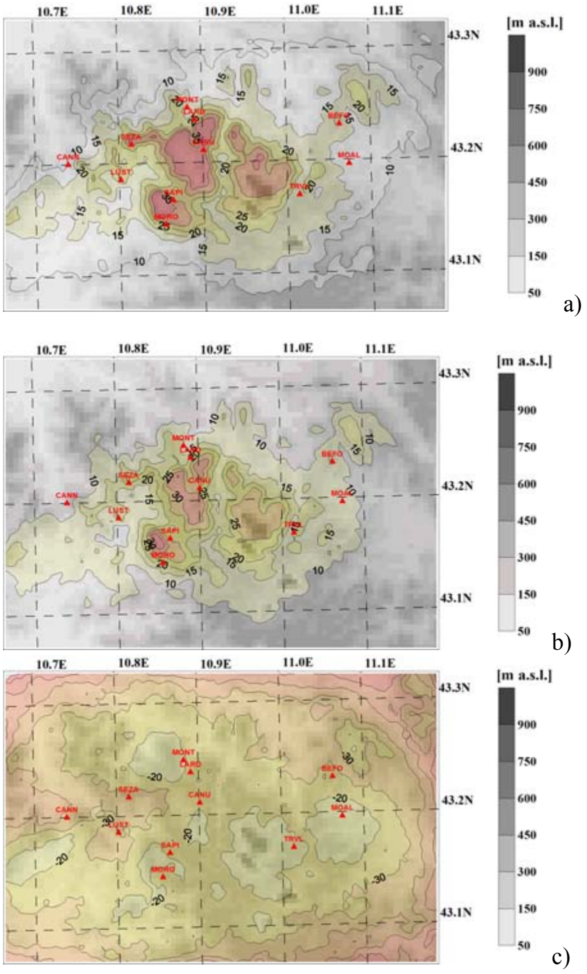

Figure 12: H_2S frequency of odor annoyances [%] from GPPS: 2003 emission scenario; b) 2007 emission scenario; c) variation.

4. CONCLUSIONS

The results achieved by the installation of AMIS® abatement systems on geothermal power plants in reducing the potential impact associated with emissions of hydrogen sulfide (H_2S) and mercury (Hg) in the Larderello-Travale-Radicondoli Geothermal Area (Tuscany) have been assessed in this paper.

The AMIS® abatement system, which has “rated values” of efficiencies up to 90% for H_2S and 95% for Hg, have been installed on new and existing geothermal power plants progressively in the frame of a program still in progress, starting from the year 2002.

This study evaluated the effects of the AMIS® spread in the geothermal both analyzing the air quality measured and by means of an air dispersion modeling exercise.

The results show a significant reduction of the GPPs contribution to the annual average concentration of H_2S and Hg. The reduction in term of odor annoyances is smaller, probably due to the less important role played by GPPs in the Traditional Area, for such issue, with respect to other emissions both natural and anthropogenic.

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