HYDROGEN SULPHIDE DISPERSION FOR HELLISHEIDI AND NESJAVELLIR GEOTHERMAL POWER PLANTS, SW-ICELAND USING AERMOD

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ABSTRACT

Hydrogen sulphide (H_2S) is a flammable, colourless gas with a characteristic odour of rotten eggs at low concentrations. At high concentrations the gas is toxic, predominantly affecting the nervous and respiratory systems. H_2S is released primarily as a gas pollutant. It spreads in the air and is accountable for causing some adverse effects to the environment. H_2S dispersion modelling of 8 hour (occupational standard), 24 hour and annual averaging periods was undertaken to assess the significant impacts in Reykjavík and Hveragerdi due to the existing Nesjavellir and Hellisheidi power plants, and from Hellisheidi's future development. The modelling results were then compared to the national standards and international guidelines and also with actual H_2S data from a continuous monitoring station. The significant impacts from the dispersion modelling reveal that the H_2S ambient concentration exceeds the standards and guidelines at several discrete receptors. Several factors affect the dispersion modelling, such as emission rate, weather conditions, elevated terrain, surface roughness, and atmospheric stability (vertical turbulence fluctuation). H_2S dispersion modelling is a unique tool for evaluating emission controls in order to minimize environmental impacts for short-term as well as long-term periods. It can be used very effectively in designing a definitive monitoring network.

1. INTRODUCTION

1.1 Background

The Hellisheidi and Nesjavellir geothermal fields are part of the Hengill geothermal area, one of the largest high-temperature geothermal fields in Iceland which covers about 110 km^2. In this area, geothermal activity is associated with three volcanic systems: the Graendalur-Hveragerdi system, the Hrómundartindur system and the Hengill system, all of which are situated in the middle of the western volcanic zone on the plate boundary between North-America and the Eurasian crustal plates (Gunnlaugsson, 2007; Orkustofnun, 2011).

Reykjavík Energy is the owner of the Hellisheidi and Nesjavellir geothermal fields and has been operating a co-generation power plant system (simultaneous production of electricity and heat from a single primary energy source) for heating purposes and generating electricity. The Hellisheidi geothermal field is located about 15 km southeast of Reykjavík; the Nesjavellir geothermal field is located about 20 km east of Reykjavík. The Hellisheidi field is now undergoing a fifth stage of development, with a focus on low- and high-temperature utilisation.

When a proposed field is developed, pollutants are usually emitted at a higher rate to the environment than before development; this can occur at the local, regional or even global scale (Morris and Therivel, 1995). One of the main environmental concerns arising from geothermal operation is the discharge of NCGs (Non-Condensable Gases) to the atmosphere. Gaseous sulphuric compounds in geothermal areas exist in the form of hydrogen sulphide (H_2S). Among all the NCG gasses emitted due to geothermal exploitation, H_2S is of the greatest environmental concern not only because of its noxious smell in low concentrations, but also its toxicity and health impacts at high concentrations and its tendency to concentrate in hollows and low lying areas due to its high density (Kristmannsdóttir et al., 2000).

The AERMOD dispersion model has completely replaced the ISC3 (Industrial Source Complex Model) model. H_2S dispersion modelling for the Hellisheidi and Nesjavellir power plants requires a various input data, including meteorological parameters. The impacts of the existing Hellisheidi power plant (4×45 MWe + $1x33$ MWe) and the existing Nesjavellir power plant (4×30 MWe), which form a part of the baseline for the expanding Hellisheidi power plant (2×45 MWe), are used in this dispersion modelling. The latest development phase of the Hellisheidi power plant will be completed with the commissioning of two 45 MWe turbines in October 2011. This study considers impacts at representative discrete receptors in Reykjavík, Hveragerdi and near the power plants (which together are representative of wider impacts), in relation to the Iceland Government Regulation No. 514/2010 regarding the concentration of hydrogen sulphide in the atmosphere. Impact assessments were undertaken using the maximum modelled H_2S concentration, based on 24-hour averaging periods. Comparing the dispersion modelling result to the H_2S continuous monitoring station in Reykjavík is imperative for evaluating emission controls and also to clarify the real role of modelling versus monitoring efforts in order to minimize environmental impacts for short-term and long-term control (Zannetti, 1990).

1.2 Objective

The purpose of this study is to assess the dispersion modelling analysis of H_2S. The results of the dispersion modelling will be compared to the national standard (H_2S ambient air and occupational standards) and guidelines (WHO). In order to accomplish this aim, the following specific objectives will be achieved:

- Assessment of the temporal and spatial distributions of H_2S due to exploitation of Hellisheidi and Nesjavellir power plants;
- Focus on atmospheric emissions of hydrogen sulphide (H_2S) for 8 hours, 24 hours and the annual averaging period;
- Prediction of H_2S concentrations due to emissions from the existing Hellisheidi and Nesjavellir power plants and Hellisheidi power plant expansion using an AERMOD dispersion model;
- Comparison of the prediction of H_2S concentrations to the H_2S data from the continuous monitoring station in Reykjavík;
- Review of study reports on any potential health and environmental impacts due to H_2S emissions from the power plants on workplaces and inhabited areas.

1.3 Previous modelling

A H$_2$S air dispersion study was conducted for the Hellisheidi power plant using AERMOD View version 5.6. The power plant had an installed capacity of about 90 MWe, producing ~180 kg/s of steam, which contained 30% H$_2$S by concentration. Since Hellisheidi power plant was commissioned on October 21, 2006, hydrogen sulphide emissions have doubled in the area from 0.007 ppm to 0.014 ppm; this increase is thought to have affected air quality in Reykjavík. Monitoring of hydrogen sulphide levels in Reykjavík showed episodes of increased concentrations before the commissioning of the power plant, and later registered up to 0.09 ppm on September 4, 2006, and up to 0.11 ppm on February 7, 2007. These increases coincided with the bleeding and testing of wells, low air temperature, high wind speed and a north-easterly wind direction in February 2007. The Gaussian models of the plume from the plant revealed that the concentrations emitted in three different periods (October 2006, November 2006 and February 2007) were reduced substantially on dispersal. The modelling results show that low gas concentrations affected Reykjavík. Only during specific meteorological conditions was it considered that station emissions affected Reykjavík's air quality (Chow Pineda, 2007). Such conditions include low air temperatures and strong, northerly winds.

2. STANDARDS

2.1 H$_2$S air ambient standard

The WHO (World Health Organization) Air Quality Guidelines, 2nd Edition 2000 set a guidance value of 150 μg/m^3 average for 24 hours, and also indicate that smell becomes a nuisance at 7 μg/m^3 over a 30 minute average.

In order to set an environmental limit for hydrogen sulphide in the atmosphere in an attempt to prevent or reduce harmful effects to the general population and on the environment, the Government of Iceland through the Ministry for the Environment issued Regulation No. 514/2010 on June 1st, 2010, regarding the concentrations of hydrogen sulphide in the atmosphere. The regulation of the concentration of hydrogen sulphide has been applied to assess the air quality impacts of the project study. The current WHO guidelines for H$_2$S and the Icelandic H$_2$S air ambient standard are presented in Table 1.

TABLE 1: H$_2$S air ambient standard

Pollutant	Averaging period	Value (μg/m^3)
World Health Organization:		
Hydrogen sulphide	24 Hour 30 Minute	150 (guideline) 7
Icelandic H$_2$S air ambient standard:		
Hydrogen sulphide	24 Hour	50 *
Hydrogen sulphide	Year	5

* The limit may be exceeded 5 times annually until June 30th 2014, after which it may not be exceeded

2.2 H$_2$S occupational standard

In addition to the ambient air quality standard described above for the protection of the general population, there are also limits for occupational settings in Iceland. The Government of Iceland through the Ministry of Welfare issued Regulation No. 320/2009 regarding pollution and the working

environment. This standard has been applied to assess air quality impacts of the project at occupational receptors. The threshold limits of chemical factors in a working environment provide occupational H_2S exposure limits from the international limit occupational safety guideline. The occupational H_2S exposure limits are presented in Table 2.

TABLE 2: Occupational safety guideline for H_2S exposure

Agency	Limit value (ppm)	Averaging period	Reference
Iceland occupational standard			
Iceland Regulation	10	TLV[1]-TWA[2] (8 hour)	No. 320/2009
International occupational standards			
ACGIH	10 15	TLV-TWA (8 hour) TLV-STEL[3] (15 Minute)	ACGIH 2009
OSHA	20	PEL-C[4,5]	OSHA 2006 29 CFR 1910.1000, Table Z-2
NIOSH	10	REL-C[6] (10 Minute)	NIOSH publ. No. 2005-149
The European Commission	5 10	TLV-TWA (8 hour) TLV-STEL (15 minute)	EC Directive 2009/161 EU, Annex EC Directive 2009/161 EU, Annex

A value of 10 ppm is equivalent to a concentration of 14,763 μg/m³
(at a pressure of 752 mmHg and a temperature of 5°C)

Exposure level definitions:
  1) TLV: Threshold Limit Values are defined as an exposure limit "to which it is believed nearly all workers can be exposed day after day for a working lifetime without ill effect".

  2) Threshold Limit Value - Time Weighted Average (TLV – TWA): the time-weighted average concentration for a conventional 8-hour workday and a 40-hour workweek, to which it is believed that nearly all workers may be repeatedly exposed, day after day, without adverse effect (ACGIH, 2009).

  3) Threshold Limit Value - Short Term Exposure Limit STEL (TLV-STEL): a 15 minute TWA exposure that should not be exceeded at any time during the work day, even if the 8-hour TWA is within the TLV – TWA. The TLV-STEL is the concentration to which it is believed that workers can be exposed continuously for a short period of time without suffering from irritation, chronic or irreversible tissue damage, dose rate dependent toxic effect or narcosis (ACGIH, 2009).

  4) PEL (Permissible Exposure Limits): are regulatory limits on the amount or concentration of a substance in the air, and they are enforceable.

  5) REL-C (Recommended Exposure Levels – Ceiling): the concentration that should not be exceeded during any part of the working exposure.

  6) Threshold Limit Value – Ceiling (TLV-C): the concentration that should not be exceeded during any part of working exposure. If instantaneous measurement is not available, sampling should be conducted for the minimum period of time sufficient to detect exposures at or above ceiling value. There is increasing evidence that physical irritation may initiate, promote or accelerate adverse health affect interaction with other chemical biological or through other mechanisms (ACGIH, 2009).

3. POWER PLANT DESCRIPTION

3.1 Geothermal energy in Hellisheidi and Nesjavellir

Icelandic geothermal resources have been divided into two types on the basis of the base temperature (maximum temperature), i.e. the reservoir temperature. The base temperature is less than 150°C for a low-temperature source and more than 200°C for a high-temperature source in the uppermost 1000 metres of depth (Orkustofnun, 2011).

Reykjavík Energy has been operating a co-generation plant combining hot water for heating purposes and generating electricity in the Hellisheidi and Nesjavellir geothermal areas. The 303 MWe geothermal power plant in Hellisheidi, Iceland was commissioned in five stages during the years 2006-2011. The first stage was completed in 2006 with two high pressure 45 MWe turbines. The second stage was completed in 2007 with one low pressure 33 MWe turbine. The third stage was completed in 2008 with two additional high pressure geothermal turbines, 45 MWe each. In 2010 a heating plant for hot water generation was added to the plant, intended for district heating; the heat output of the first stage is 133 MWt and two further 133 MWt stages are to follow later. In 2011 the 5th stage of the plant is being prepared for commission which includes two high pressure geothermal turbines, 45 MWe each. The Nesjavellir power plant was built in several stages. Hot water production for district heating in Reykjavik started in 1990. Electricity production started in 1998 with a 60 MWe turbine. In 2001, it was extended to 90 MWe. Currently, Nesjavellir power plant generates about 120 MWe of electricity (since 2005) and 300 MWt for district heating.

3.2 Process and operation

The Hellisheidi power plant is a flash steam, combined heat and power plant (CHP). The plant utilizes approximately 500 kg/s of 180°C geothermal steam for electrical generation. The layout of the electricity production is presented in Figure 1. The hot fluid is extracted from 49 wells, 2000-3000 metres deep; the geothermal water is utilised for hot water production and the steam is used for generating electricity. The fluid from the well goes through a production pipeline into a separator unit, and then

FIGURE 1: Layout for electricity production

steam flows to the system. The pressure in the steam pipe is controlled by opening a control valve and releasing the steam through the hood. The steam separator unit separates steam from the water, and the water falls down while the steam flows above into a mist separator (demister) for drying and cleaning before entering the turbines. After turning the turbines, the steam goes through a condenser where the steam is cooled and condensed by being sprayed by cold water from the cooling tower. The cooling water is heated up in this process and then cooled back in a wet cooling tower of the counter flow type.
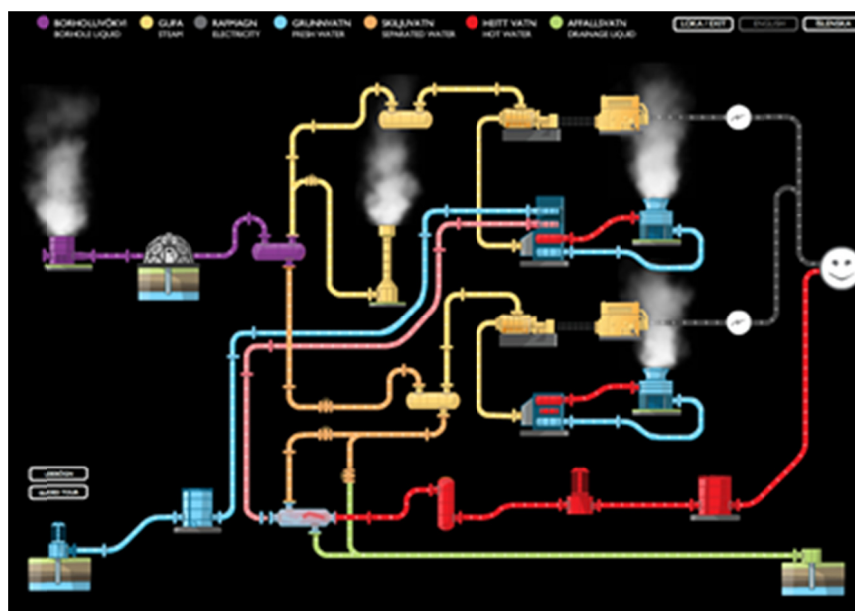
3.3 Emission of hydrogen sulphide

In a geothermal power plant, the gas chemistry analytical results indicate that carbon dioxide (CO_2) is the major gas component in all cases, followed by H_2S and other gases (H_2, N_2, Ar, O_2 and CH_4). The concentrations of the gases can vary depending on the production field. The total amount of gas emissions from Hellisheidi power plant in the year of 2010 were just over 56,400 tons, of which carbon dioxide (CO_2) accounted for 42,334 tons and the amount of hydrogen sulphide (H_2S) was 13,600 tons (Gunnlaugsson, 2011a). Meanwhile, the gas releases from Nesjavellir power plant were 28,918 tons (CO_2) and 9,384 tons (H_2S) (Gunnlaugsson, 2011b).

In the power plants, gas is released from steam in three ways: (1) in a condenser in the power plant building, steam is condensed after exiting the turbines of the power plant. Due to the high concentration of various gases in the steam, only a small fraction is dissolved in the condensate. The gases, therefore, exit in a gaseous phase and are sucked out of the condenser with powerful vacuum generating equipment, and are then released into the atmosphere through special stacks or the cooling towers; (2) steam is released in a small part from stacks by the separator station to control the steam pressure in the power plant; (3) during exploration and construction of a power plant, the wells discharge gases to silencers and also during service maintenance. After a power plant is operational, the flow is directed to silencers only under exceptional circumstances, usually for production tests of new wells or other tests (Gunnlaugsson, 2011a; 2011b). In general, the greatest release of H_2S concentration is from condensers by the power plant building through the cooling tower. The variability of the concentration depends on how many wells are being drilled, how many are being flow tested, and on the number of silencers. The steam flow rate and H_2S amounts released from Hellisheidi and Nesjavellir power plants are presented in Table 3.

TABLE 3: Amount of H_2S released from Hellisheidi and Nesjavellir power plants
(Reykjavik Energy, 2011)

Power plant	Steam flow rate (kg/s)	H_2S concentration in steam (mg/kg)	H_2S amount released (g/s)
Nesjavellir power plant 120 MWe & 300 MWt	216	1,268	274
Hellisheidi power plant 213 MWe & 133MWt	334	1,109	368
Hellisheidi power plant 303 MW and 213MWt	576	1,109	639

4. PHYSICAL PROPERTIES AND IMPACTS OF H_2S

4.1 Physical properties of H_2S

Hydrogen sulphide (H_2S) is a flammable, colourless gas with a characteristic odour of rotten eggs at low concentrations of 0.3 ppm (Waldron H.A, 1990). Its molecular weight is 34.08. It is heavier than air and slightly soluble in water and acts as a weak acid. A mixture of H_2S and air is explosive. Hydrogen sulphide occurs both naturally and from human processes. H_2S is oxidized by photochemical generated free radicals, especially by hydroxyl radicals, forming the sulfhydryl radical and ultimately sulphur dioxide or sulphate compounds (WHO, 2003). The atmospheric resident time of H_2S is typically less than 1 day, but may be as high as 42 days in winter (WHO, 2003). The resident time varies depending on the presence of photoactive pollutants, temperature, and the geographic differences in where the concentrations are found. The physical properties of H_2S are presented in Table 4.

TABLE 4: Physical properties of H$_2$S (Wikipedia, 2011; WHO 2000; 2003)

Description	H$_2$S properties
Molar mass	34.08 g/mole
Exact mass	33.987720754 g/mol
Appearance	Colourless gas
Density	1.45 g/m^3
Melting point	-82°C, 191 K, -116°F
Ignition temperature	260°C
Flash point	-82°C
Flammability limits in air	4.3-46%
Boiling point	-60°C, 213 K, -76°F
Vapour pressure	740 kPa (at 21°C)
Odour	Odour of rotten eggs

4.2 H$_2$S impact

Hydrogen sulphide is released primarily as a gas pollutant and spreads in the air as a contaminant, accountable for causing some adverse effects to the environment (Zannetti, 1990). An odour annoyance occurs at a concentration exceeding 7 μg/m^3 (30-minute averaging period) (WHO, 2000). A number of studies have been conducted related to effects on vegetation at geothermal power plants: e.g. at Mt. Amiata (Tuscany Italy) it was shown that sensitive plant species might be affected by an exposure to 100 μg/m^3 hydrogen sulphides (Bacci et al., 1999); a similar study on vegetation also found that there was no observable effect with a concentration of less than 140 μg/m^3 for long-term H$_2$S exposure (Idriss et al., 2004). Concentrations of H$_2$S at 150 μg/m^3 have little effect on vegetation; however, low levels of H$_2$S exposure (45μg/m^3) can increase plant growth and the rate of physiological processes in a variety of species, sometimes termed a fertilizer effect.

The hydrogen sulphide gas is classified among asphyxiant gasses; inhalation through the respiratory system is the major route of entrance into the human body, both in workplaces and in the ambient air. Health effects depend upon the type and amount of pollutants present, the durations of exposure, and the state of health, age and level of activity of the person exposed (Morris and Therivel, 1995; OSHA, 2005). The H$_2$S exposures range in effect from minor irritation with effects on both oxygen utilization and the central nervous system through serious illness to premature death in extreme cases (Hansel and Oppenheimer, 2004). Hydrogen sulphide is not considered to be a cumulative poison because it is rapidly metabolised to harmless sulphates and excreted by the kidneys to be readily eliminated from the body (Ammann and Greenberg, 1993). Hydrogen sulphides have not been classified as having carcinogenic effects on humans (ATSDR, 2006).

The hazards caused by high concentrations of hydrogen sulphide are relatively well known, but information on possible harmful effects over a a long term, and of very low concentrations on humans is scanty (Rom, 1998). Exposure symptoms and signs of hydrogen sulphide intoxication are most often caused by relatively high concentrations in occupational exposures. Low-level concentrations can occur more or less continuously in certain industries such as in viscose, rayon and pulp production, at oil refineries and in geothermal energy installations (WHO, 2003). The LOAEL (lowest observed adverse effect level) can cause eye irritation at 15 mg/m^3 (10 ppm) (WHO, 2000); another effect of low concentrations gives a sensation of irritation to the nose, throat, and respiratory system, e.g. burning or tearing of eyes, coughing, and shortness of breath (Hansel and Oppenheimer, 2004). Conjunctiva irritation is the next subjective symptom and can cause so called "gas eye" at hydrogen sulphide concentrations of 70-140 mg/m^3 (50-100 ppm) (WHO, 2000). High concentrations can cause shock, convulsions, inability to breathe, extremely rapid unconsciousness, coma and death. Effects can occur within a few breaths, and possibly a single breath (OSHA, 2005). As part of the asphyxiant gasses, hydrogen sulphide binds to and inactivates cytochrome oxidisation in

mitochondria; the gas essentially displaces oxygen from alveoli and causes death (Wallace, 1998; WHO, 2000). However, in many individuals, there may be permanent or long-term effects such as headaches, poor attention span, poor memory, and poor motor function. Hydrogen sulphide concentrations of 210 mg/m^3 (150 ppm) can quickly paralyze the sense of smell, and people may then be unaware of danger. Instantaneous death has occurred at levels of 14,000 mg/m^3 (1000 ppm). Table 5 shows the established dose effect relationships for hydrogen sulphide.

TABLE 5: Dose effect relationships for hydrogen sulphide (WHO, 2003)

Hydrogen sulphide concentrations		Effect
mg/m^3	ppm	
	2000+	Immediate loss of consciousness and high probability of death
1400 - 2800	1000-2000	Immediate collapse with paralysis of respiration
750-1400	530-1000	Strong central nervous system stimulation, hyperpnoea following by respiratory arrest
450-750	320-530	Pulmonary oedema with risk of death
	500	Very dangerous, evacuation should occur well below this level
210-350	150 – 250	Loss of olfactory sense (irritation of upper respiratory tract, sense of smell lost)
70-140	50-100	Serious eye damage
	60	Prolonged exposure may cause conjunctivitis and eye pain
	50	Prolonged exposure may cause pharyngitis and bronchitis
	20	Sense of smell to gas lost. Concentrations tolerated for some hour without harm
15-30	10-20	Threshold of eye irritation
	0.008-0.2	Olfactory threshold -"rotten eggs" smell detectable

5. METHODOLOGY

5.1 Theoretical approach to air dispersion

The Gaussian plume model is the most common air pollution model for single and multiple sources. It is based on an equation that describes a three dimensional concentration field generated by a point source under stationary meteorological and emission conditions. Air pollutant plume dispersion equations have been undertaken by numerous researchers. By performing a mass balance on a small control volume, a simplified diffusion equation, which describes a continuous cloud of material dispersing in a turbulent flow, can be written as (Macdonald, 2003):

$$\frac{\partial C}{\partial t} + U\frac{\partial C}{\partial x} = \frac{\partial}{\partial y}\left(K_y\frac{\partial C}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_z\frac{\partial C}{\partial z}\right) + S \tag{1}$$

where x = Along-wind coordinate measured in wind direction from the source;
     y = Cross-wind coordinate direction;
     z = Vertical coordinate measured from the ground;
     $C(x,y,z)$ = Mean concentration of diffusing substance at a point (x,y,z) (kg/m^3);
     K_y, K_z = Diffusivities in the direction of the y- and z- axes (m^2/s);
     S = Source/sink term (kg/m^{3}s);
     U = Mean wind velocity along the x-axis (m/s).

A term by term interpretation of Equation 1 is:

$\dfrac{\partial C}{\partial t} + U\dfrac{\partial C}{\partial x}$ Time rate of change and advection of the cloud by the mean wind;

$\dfrac{\partial}{\partial y}\left(K_y\,\dfrac{\partial C}{\partial y}\right)$ Turbulent diffusion of material relative to the centre of the pollutant cloud;

S Source term which represents the net production (or destruction) of pollutants due to sources (or removal mechanism).

In deriving Equation 1, it is assumed that the pollutant concentrations do not affect the flow field (passive dispersion), molecular diffusion and longitudinal (along-wind) diffusion are negligible, flow is incompressible, wind velocities and concentrations can be decomposed into a mean and fluctuating component with the average value of the fluctuating (stochastic) component equal to zero, turbulent fluxes are linearly related to the gradients of the mean concentrations and the mean lateral (V) and vertical (W) wind velocities are zero.

An analytical solution to Equation 1 gives the Gaussian plume model. For a continuous point-source released at the origin in a uniform (homogenous) turbulent flow, the solution to Equation 1, as given by Macdonald (2003), is:

$$C(x,y,z) = \frac{Q}{4\pi x\,\sqrt{K_y K_z}}\,exp\left(\frac{-y^2}{4K_y\,(x/U)}\right)exp\left(\frac{-z^2}{4K_z\,(x/U)}\right) \tag{2}$$

where Q = Source pollutant emission rate.

The turbulent diffusivities K_y and K_z are unknown in most flows; in the atmospheric boundary layer K_z is not constant, but increases with height above the ground. In addition, K_y and K_z increase with distance from the source, because the diffusion is affected by different scales of turbulence in the atmosphere as the plume grows. If we define the lateral dispersion coefficient function, σ_y, as follows:

$$\sigma_y = \sqrt{2K_y\frac{x}{U}} \tag{3}$$

Then the final form of the Gaussian plume equation, for an elevated plume released at $z = H_p$ is:

$$C(x,y,z) = \frac{Q}{2\pi U_p \sigma_y \sigma_z}\,exp\left(-\frac{y^2}{2\sigma_y^2}\right)\left[exp\left\{-\frac{(z-H_p)^2}{2\sigma_z^2}\right\} + exp\left\{-\frac{(z+H_p)^2}{2\sigma_z^2}\right\}\right] \tag{4}$$

where the vertical diffusion coefficient function is σ_z.

In this expression, a second z-exponential term has been added to account for the fact that a pollutant cannot diffuse downward through the ground at $z = 0$, but is assumed to be reflected. This "image" term can be visualised as an equivalent source located at $z = -H_p$ below the ground. Equation 4 is the Gaussian plume formula for a continuous point source. The plume height H_p is the sum of the actual stack height H_s plus any plume rise ΔH due to initial buoyancy and momentum of the release. The wind speed U_p is taken to be the mean wind speed at the height of the stack. Considering concentrations at ground level (where receptors such as people are), z is assumed to be zero (Macdonald, 2003), as follows:

$$C(x, y, z = 0) = \frac{Q}{\pi U_p \sigma_y \sigma_z} exp\left(-\frac{y^2}{2\sigma_y^2}\right) exp\left(-\frac{H_p^2}{2\sigma_z^2}\right) \tag{5}$$

A general non-Gaussian model, which allows for vertical variation, is expressed as:

$$C(x, y, z) = \frac{Q}{\sqrt{2\pi} U_p \sigma_y} exp\left(-\frac{y^2}{2\sigma_y^2}\right) f(z) \tag{6}$$

Here f(z) is a normalized function that describes the vertical distribution of the material in the plume. The rate of transfer of a pollutant through any vertical plane downwind from the source is a constant steady state, and this constant should equal the emission rate of the source, *Q*. Thus:

$$\iint\limits_{y,z} CU \, dydz = Q \tag{7}$$

where the integration is performed over the *y-z* plane, perpendicular to the plume axis.

5.2 Model description

AERMOD is a new generation of dispersion modelling initiated by The American Meteorological Society (AMS) and the U.S. Environmental Protection Agency (EPA) with the design goal of introducing modelling of planetary boundary layer turbulence structures, scaling and concepts into regulatory dispersion models.
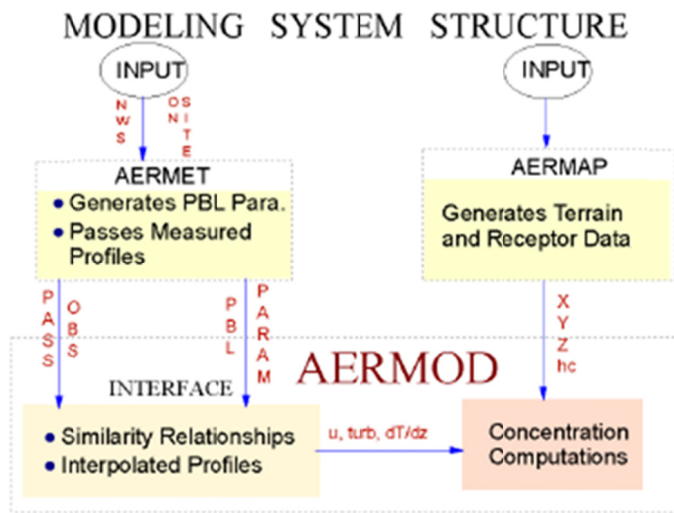

FIGURE 2: Data flow in AERMOD modelling system (Cimorelli et al., 2004)

AERMOD is a steady state plume model, designed to estimate near-field as less than 50 km (U.S. EPA, 2004) and run with a minimum of observed meteorological parameters as a replacement for the ISC3 (Industrial Source Complex) model. AERMOD was designed to treat both surface and elevated sources in simple and complex terrain. Special features of AERMOD include its ability to treat the vertical heterogeneity of the planetary boundary layer, special treatment of surface releases, irregularly-shaped area sources and the limitation of vertical mixing in the stable boundary layer. The modelling system structure of AERMOD is presented in Figure 2.

The AERMOD modelling system consists of two pre-processors and a dispersion model. The meteorological pre-processor (AERMET) provides AERMOD with the meteorological information to characterize the planetary boundary layer. The input data of AERMET, as described by Cimorelli et al. (2004), consists of surface roughness, albedo and bowen ratios, plus standard meteorological observations including wind speed, wind direction, temperature and cloud cover. AERMET then calculates the planetary boundary layer parameters which include friction velocity, Monin-Obukhov length, convective velocity scale, temperature scale, mixing height, and surface heat flux. These

scaling parameters are used to construct vertical profiles of wind speed, lateral and vertical turbulent fluctuations, potential temperature gradients, and potential temperature.

AERMAP is a terrain pre-processor designed to simplify and standardise the input of terrain data for AERMOD. AERMAP uses gridded terrain data for the modelling area to calculate a representative terrain-influence height associated with each receptor location. The terrain pre-processor can also be used to compute elevations for both discrete receptors and receptor grids. AERMOD handles the computation of pollutant impacts on both flat and complex terrain within the same modelling framework (Cimorelli et al., 2004). The version used for this assessment is AERMOD View Version 7.1.0 supplied by Lake Environmental Software released in May 2011.

The dispersion modelling for this study used the default regulatory dispersion option for H_2S concentration output. The Universal Transverse Mercator (UTM) projection for zone 27 North of the equator was employed using the world geodetic system of 1984 (WGS-84). The prediction of H_2S concentrations was simulated using an 8-hour, 24-hour and annual average time periods. Rural classification was selected based upon land use procedures with a circumstance of 3 km radius circle from the emission source (ADEQ, 2004). This AERMOD classification considers different rates of dispersion, turbulent mixing and buoyancy induced mixing.

6. BACKGROUND DATA FOR DISPERSION MODELLING

6.1 Meteorological data

The major meteorological factors that affect air ambient pollution are as follows:

- Wind speed direction, which is generated by a geostrophic wind component. Wind direction determines the sector of the compass into which the plume is dispersed. Wind speed affects the distance which the plume travels over time and can affect plume dispersion by increasing the initial dilution of pollutants and inhibiting plume rise;
- Atmospheric stability is a measure of the turbulence of the air, and particularly of vertical motion which affects the dilution rate of pollutants (Zannetti, 1990).

The minimum parameters of meteorological data suitable for dispersion modelling purposes include wind speed, wind direction, cloud cover, ceiling height and temperature. The meteorological parameters required for dispersion modelling are surface observation data and upper air observation data. The data collected from the weather station were analysed to select the most representative and relevant information necessary for the purposes of this study. The most representative (covering Hellisheidi and Nesjavellir power plants) observing station of the proposed project study which was able to provide data of suitable quality and format is Ölkelduháls weather station No.1493, located approximately 7 km east of Hellisheidi power plant. This station provided profile meteorological data of wind direction, wind speed, temperature, precipitation, with the exception of cloud cover which was provided by Reykjavík station No.1, the station located approximately 26 km northwest of Hellisheidi power plant. Upper air data (mixing height) were taken from AERMAP calculations based on hourly meteorological data. Standard meteorological data pre-processing accounts for site specific parameters such as land characteristics (albedo, surface roughness, bowen ratio, etc.).

One year of hourly sequential data from January to December 2010 (Icelandic Meteorological Office, 2011) was used as input data for the dispersion modelling (Scenarios A and B). A wind rose of Ölkelduháls station was constructed for one year of meteorological data. In Figure 3, the wind rose shows a predominantly north-easterly direction with a velocity ranging from calm winds 0.5-2.1 m/s within which a 4.37% frequency was distributed. The highest wind velocity distributed 25.4 % with a 5.7-8.8 km/s wind velocity. A previous study of dispersion modelling in Hellisheidi power plant
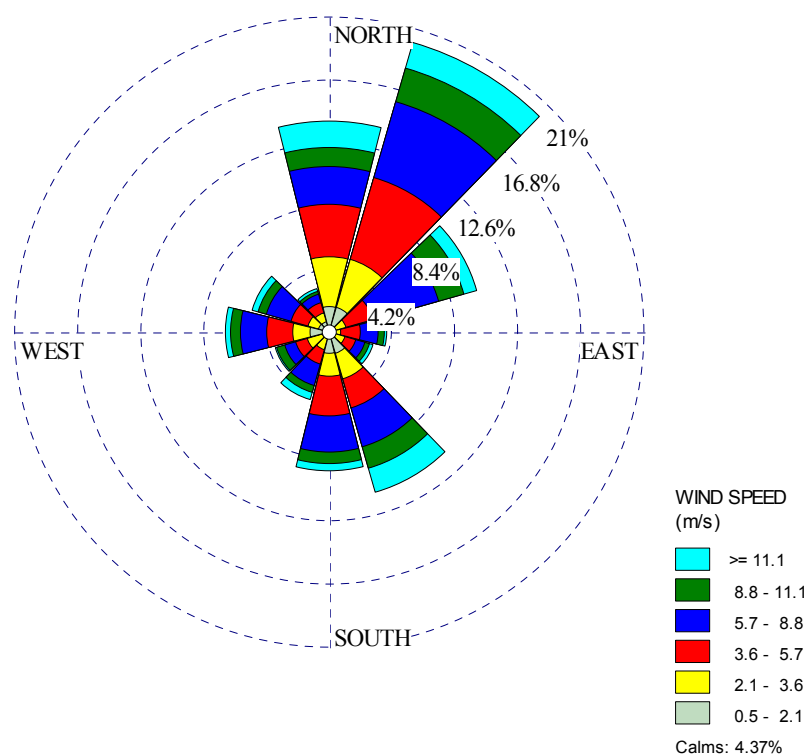
reported the same pattern of wind direction, predominantly north-easterly for the period of October 2006 to February 2007. The highest wind velocity frequency distributed 23.9% with a 2.4-3.9 m/s wind velocity. The meteorological data was taken from Hellisheidi weather station No.31392 (Chow Pineda, 2007).

FIGURE 3: Wind rose for the period January-December 2010

6.2 Terrain and surface roughness

Terrain is one of the factors that affects air pollution phenomena where atmospheric vertical motion is due to a low- or high-pressure system or complex terrain effect (hill, mountain, 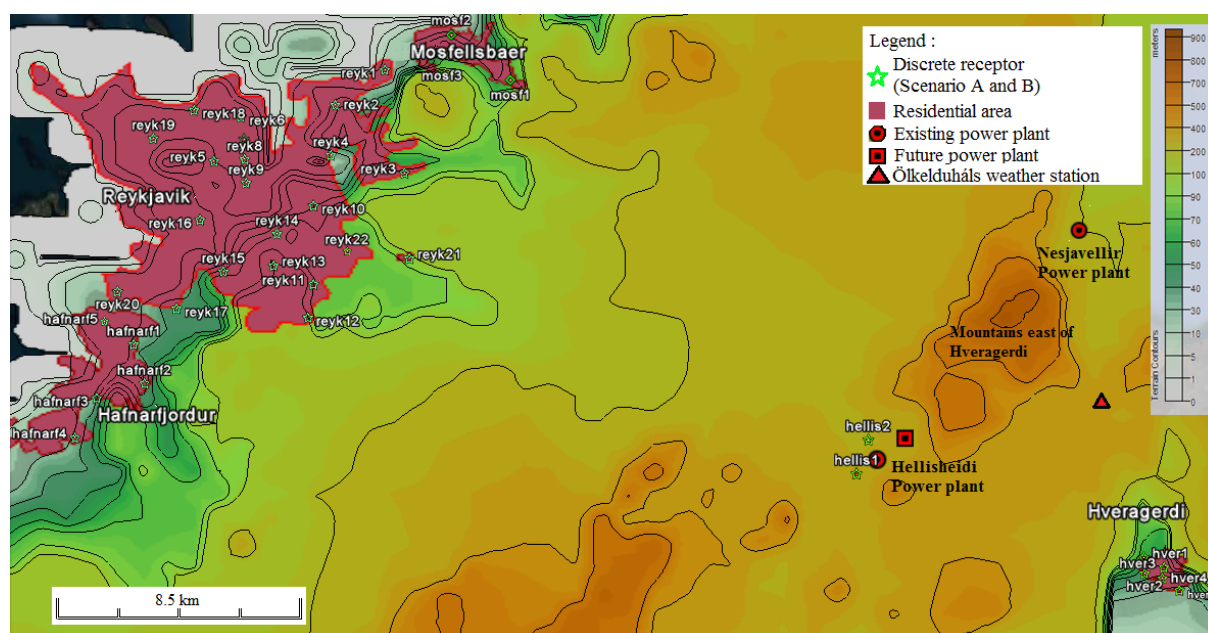ranges) and elevation above the ground (Zannetti, 1990). The presence of elevated terrain can significantly affect ground level concentrations of air pollutants emitted from elevated sources such as stacks or cooling towers, by reducing the distance between the plume's centre line and ground level and increasing turbulence and funnelling of plumes around topographical features.

A detailed digital elevation model of the terrain was supplied by ISOR (Iceland GeoSurvey) and used directly in the dispersion model. The roughness of the terrain over which a plume passes can have a significant effect on dispersion by altering the velocity profile with height, and the degree of atmospheric turbulence. This is accounted for by a parameter called the surface roughness length.

Considering the geographic conditions of the project study, the elevated option was chosen in the model. The terrain elevation view of the project study is represented in Figure 4.

6.3 Building downwash

The movement of air over and around buildings generates areas of flow circulation which can lead to increased ground level concentrations in the buildings' wake. Downwash effects can be significant, where building heights are greater than about 30 - 40% of the stack height (Boyland et al., 2011) and the near distance is less than 1 km from the emission source (Zannetti, 1990); the down wash effect of the plume is caused by building aerodynamics.

AERMOD contains a calculation model that determines building impacts on air flows which, in turn, affect dispersion around the power plant. The only buildings likely to affect dispersion are the power house and the cooling tower structure of the existing Nesjavellir and Hellisheidi power plants and in Hellisheidi's future development. Rectangular and polygonal buildings were selected for this project study to define the location and dimension of the power house building and cooling tower structure in

FIGURE 4: Elevation of the terrain in the study region

input dispersion modelling. The three dimensional (3D) view of Hellisheidi´s building structures in the model and the building dimensions are presented in Figure 5 and Table 6.
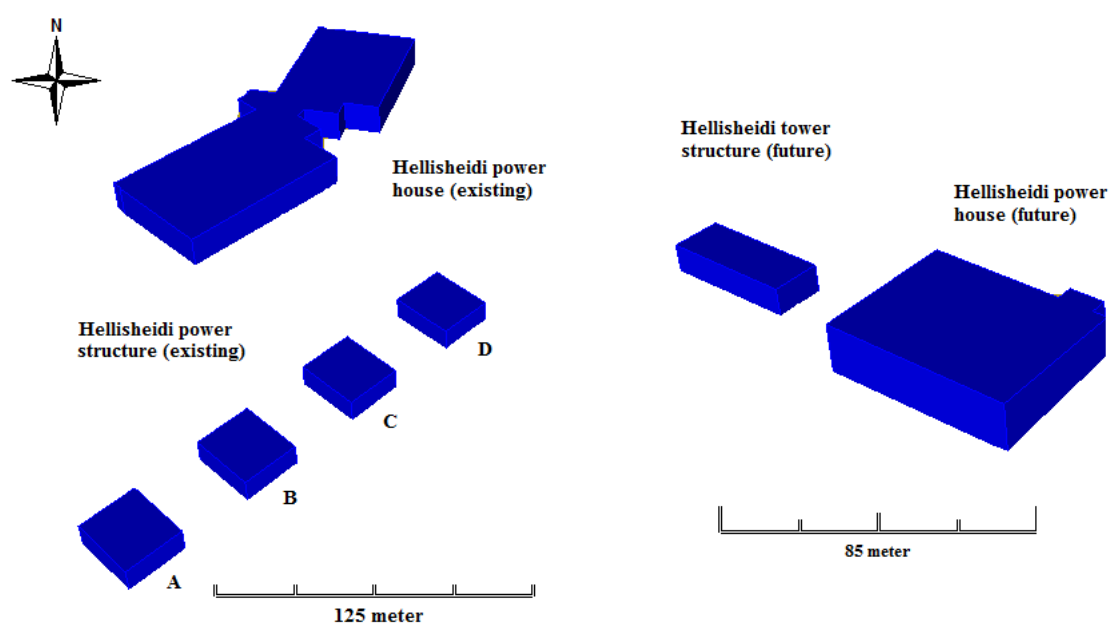

FIGURE 5: Three dimensional (3D) view of Hellisheidi's building structure in the model

6.4 Modelled scenario and key input data

The following scenarios were identified for H_2S dispersion modelling:

- Scenario A: H_2S air quality impact of the existing Hellisheidi power plant and the existing Nesjavellir power plant;
- Scenario B: H_2S air quality impact of Hellisheidi's future development in addition to the existing power plants.

TABLE 6: Modelled building properties

Building	Height (m)	Width (m)	Length (m)	Elevation (m)*
TS Nesjavellir (existing)	9.7	18	60	178
Nesjavellir power house (existing)	13.18, 15.05	50	73	180
TS Hellisheidi A (existing)	11	33	28	269
TS Hellisheidi B (existing)	11	33	28	269
TS Hellisheidi C (existing)	11	33	28	269
TS Hellisheidi D (existing)	11	33	28	269
Hellisheidi power house (existing)	18	70	98	265
TS Hellisheidi (future)	10.7	17	50	280
Hellisheidi power house (future)	18	70×2	98×2	280

Explanation: TS: Tower structure; *Elevation used by AERMAP

6.4.1 Scenario A

The purpose of the baseline modelling is to predict the impacts of H_2S emissions from the existing Hellisheidi and Nesjavellir power plants which will then be compared to the actual H_2S emissions measured at the Grensásvegur station (operated by Umhverfisstofnun – Environment Agency of Iceland). In Scenario A, the model represents normal operation of the existing Hellisheidi and Nesjavellir power plants, where the maximum release of emission rates from the cooling towers located at the power plants were modelled, by assuming full load operation capacity for a whole year without considering yearly maintenance or overhaul (when the power plant is shut down for a certain period).

The representative background air ambient concentrations in the vicinity of the project study were considered in this dispersion modelling; a H_2S background concentration of 0.004 ppm (0.0059 μg/m^3, calculated based on 752 mm Hg local average pressure and 5°C temperature) in the vicinity of Hellisheidi power plant was identified from the previous H_2S air dispersion study (Chow Pineda, 2007). Due to the presence of natural H_2S sources in the study area, it is likely that the actual 24 hour concentrations experienced would fluctuate above and below this value; in fact, the modelling input background concentrations of H_2S doubled to 0.008 ppm (0.012 μg/m^3), calculated based on 752 mm Hg local average pressure, and 5°C temperature.

In order to account for the benefit of combined buoyancy from having the towers next to each other (which is not accounted for by default in the model), four towers in each block in the existing Hellisheidi power plant were grouped into a virtual stack, combining the H_2S gaseous discharge of all four towers, based on the layout and dimensions as well as the existing Nesjavellir power plant. The source input model scenario A is provided in Table 7.

6.4.2 Scenario B

Scenario B represents normal operation of Hellisheidi's future development, considering a maximum emission rates from the cooling towers located at the power plant, and assuming full load operation capacity for a whole year as described previously.

In order to account for the benefits of combined buoyancy from having the towers next to each other (which is not accounted for by default in the model), the four towers in one block tower in Hellisheidi future development were grouped into a virtual stack, combining the H_2S gaseous discharge of all four towers. As described above, the results from Scenario B include the consideration of air ambient concentrations present in the baseline (i.e. contributions from the existing power plant of Hellisheidi and Nesjavellir power plant and background concentrations). The source input model scenario B is presented in Table 8.

TABLE 7: Source input model scenario A

Source	X (m)	Y (m)	H₂S flow (g/s)	Release height (m)	Tempera-ture (°C)	Exit velocity (m/s)	Diameter (m)	Base elevation (m a.s.l.)
Hellisheidi – existing power plant (213 MWe)								
Combined CT Hellisheidi A	480379	7100938	106	13.8	7	8.5	39.6	269
Combined CT Hellisheidi B	480424	7100978	106	13.8	7	8.5	39.6	258
Combined CT Hellisheidi C	480467	7101019	106	13.8	7	8.5	39.6	258
Combined CT Hellisheidi D	48051	7101060	106	13.8	7	8.5	39.6	258
Nesjavellir – existing power plant (120 MWe)								
Combined CT Nesjavellir	487593	7109046	296	13	7	9.6	35.6	177

Coordinates in UTM Zone 27, Northern Hemisphere; CT: Cooling tower

TABLE 8: Source input scenario B

Source	X (m)	Y (m)	H₂S flow (g/s)	Release height (m)	Tempera-ture (°C)	Exit velocity (m/s)	Diameter (m)	Base elevation (m a.s.l.)
Hellisheidi power plant – future development (303 MWe)								
Combined CT Hellisheidi	481317	7101961	212	13.5	7	8.5	39.6	280

Coordinates in UTM Zone 27, Northern Hemisphere; CT: Cooling tower

6.5 Receptors and grid

Reykjavík area is the largest inhabited area closest to the power plants; there is a population of approximately 118,326 in the city (Statistics Iceland, 2011); other areas nearby include Mosfellsbaer and Hafnarfjördur with approximate populations of 8,479 and 25,913, respectively. Hveragerdi is another area near the power plants with a population of approximately 2,291.

The discrete receptors' Cartesian coordinates and grid were identified in the modelling to determine areas of maximum predicted H₂S concentrations for scenario A (baseline) and scenario B (future development) which are then compared to the respective standards and guideline. This identification of inhabited areas in Reykjavík, Hveragerdi and the vicinity of the power plants was carried out through a review of satellite mapping for the project study area. An elevation profile for each receptor was also performed in the modelling. The coordinates and layout of discrete receptors are presented in Table 9 and Figure 6.

In order to provide a high resolution of predicted concentrations close to the power plant (where concentrations can vary greatly over a smaller distance) and allow coverage over a wider area up to 42 km from the modelled source, the following three grid sizes and resolutions were used together:

- Grid 1 – 42 km × 42 km at 300 m resolution;
- Grid 2 – 20 km × 20 km at 300 m resolution; and
- Grid 3 – 2.25 km × 2.25 km at 20 m resolution.

TABLE 9: Discrete receptor coordinates

No.	Receptor	Easting (m)	Northing (m)	Elevation (m)
1	Mosfellsbaer 1	467893	7114497	56.43
2	Mosfellsbaer 2	465833	7116113	40.23
3	Mosfellsbaer 3	465502	7114665	73.87
4	Reykjavík 1	463464	7114946	27.8
5	Reykjavík 2	461714	7113725	58.62
6	Reykjavík 3	464153	7111293	80
7	Reykjavík 4	461533	7111969	20.11
8	Reykjavík 5 (Grensásvegur)	457418	7111805	30
9	Reykjavík 6	458372	7113353	20
10	Reykjavík 7	458466	7112569	27
11	Reykjavík 8	458482	7111865	26.28
12	Reykjavík 9	458528	7111036	17.6
13	Reykjavík 10	460938	7110187	60.83
14	Reykjavík 11 (near Lake Ellidavatn)	460932	7107439	91.35
15	Reykjavík 12	460723	7106278	91.27
16	Reykjavík 13	459559	7108101	100
17	Reykjavík 14	459650	7109222	68.6
18	Reykjavík 15	457744	7107922	54.93
19	Reykjavík 16	456941	7109738	66.57
21	Reykjavík 17	456054	7106644	42.09
21	Reykjavík 18	456721	7113606	10
22	Reykjavík 19	455286	7112625	20
23	Reykjavík 20	453948	7107263	35.05
24	Reykjavík 21	464300	7108305	108.15
25	Reykjavík 22	462116	7108583	80
26	Hafnarfjordur 1	454533	7105403	35.22
27	Hafnarfjordur 2	454885	7104028	32.33
28	Hafnarfjordur 3	453210	7103534	40.49
29	Hafnarfjordur 4	452419	7102150	28
30	Hafnarfjordur 5	453483	7106220	29.98
31	Hellisheidi 1	479695	7100722	271
32	Hellisheidi 2	480174	7101869	260
33	Hveragerdi 1	487559	7109051	53.21
34	Hveragerdi 2	487517	7109116	47
35	Hveragerdi 3	487244	7108656	44.73
36	Hveragerdi 4	488003	7109875	37.44
37	Hveragerdi 5	489920	7097589	30

Coordinates in UTM Zone 27, Northern Hemisphere

6.6 H$_2$S measurement monitoring

The H$_2$S continuous monitoring stations were built based on the operation of Hellisheidi and Nesjavellir power plants, in Reykjavík and in the vicinity of the power plants. The first H$_2$S continuous monitoring station was built on 22nd February 2006 at Grensásvegur in Reykjavík (Ólafsdóttir et al., 2010); this station is operated by Umhverfisstofnun – The Environment Agency of Iceland (http://loft.ust.is/). Additional H$_2$S continuous monitoring stations were built in the vicinity of the power plant and the nearest inhabited area (Nordlingaholt and Hveragerdi); these stations are operated by Sudurland Health Agency (www.heilbrigdiseftirlitid.is/).
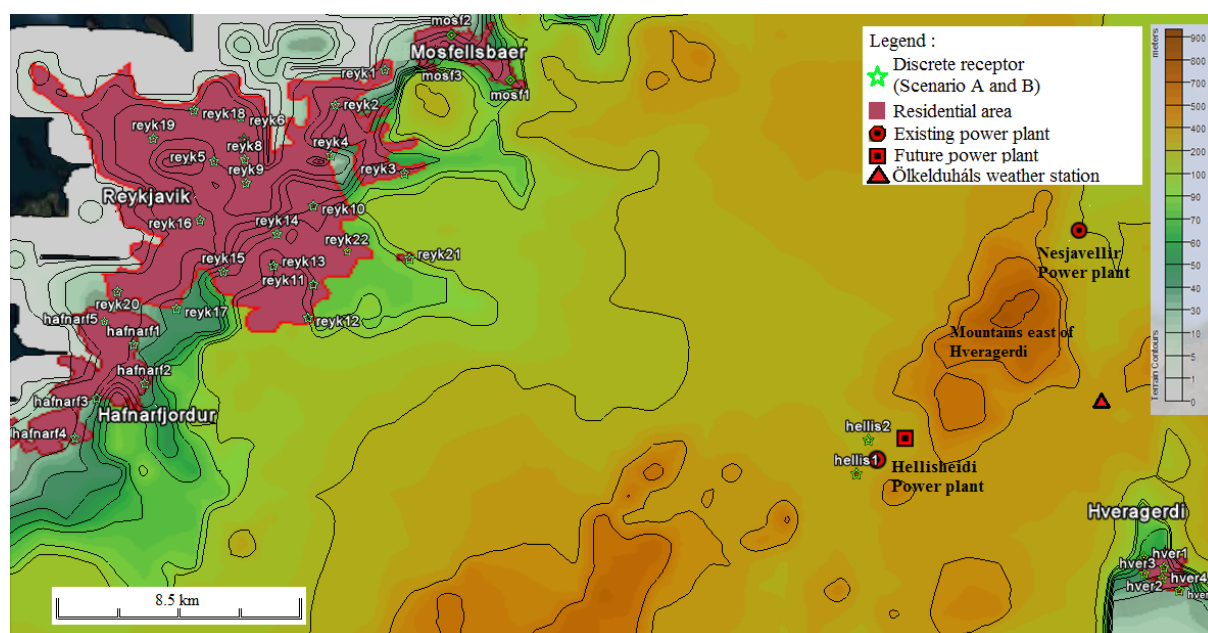
FIGURE 6: Discrete receptor layout

Data from the H_2S continuous monitoring station at Grensásvegur in Reykjavík were compared with the dispersion modelling results from the existing Hellisheidi and Nesjavellir power plants (baseline) and Hellisheidi power plant future development. Data from years 2006, 2008 and a whole picture of 2006-2011 (up until September) are presented in relation to power plant development and modelling comparisons.

Figure 7 shows the levels of H_2S concentrations for one year of monitoring data from January to December 2006, as a baseline of the monitoring data. The H_2S concentration increases were relatively high when Hellisheidi power plant, with a total installed capacity of 90 MWe, started operation on October 2006. H_2S concentrations before October 2006 reflect emissions from the Nesjavellir power station, which has been in operation since 1990.
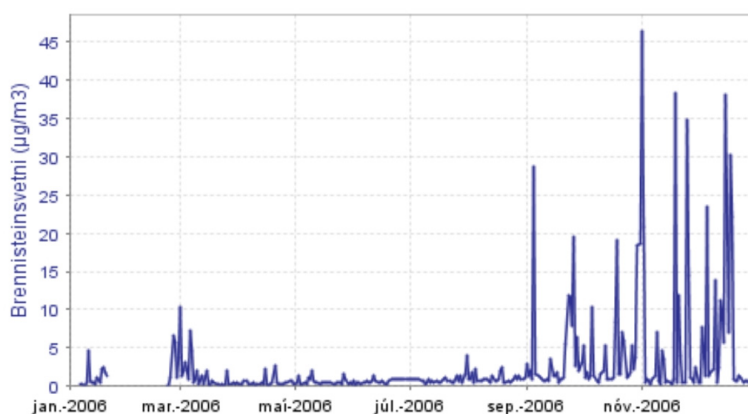
FIGURE 7: H_2S concentrations in January-December 2006, averaged over 24-hour periods (Environment Agency of Iceland, 2011)

In the fall of 2008, Hellisheidi power plant was enlarged to a total installed capacity of 213 MWe. The level of H_2S concentrations for one year of data monitoring from January to December 2008 is presented in Figure 8. H_2S concentrations for the period of May to August 2008 were not considered since the H_2S continuous monitoring station's measuring device was not working properly. Concentrations of H_2S over a 24 hour mean in Reykjavík were below the WHO guideline (150 μg/m³ averaged over a 24 hour period). Nevertheless, the highest concentrations in the beginning of January 2008 exceeded the Iceland H_2S air ambient standard value (50 μg/m³ averaged over 24 hours) (Ministry for the Environment, 2010). It should be noted that meteorological conditions, especially during the wintertime, determine H2S concentrations in far-field locations such as Reykjavík.
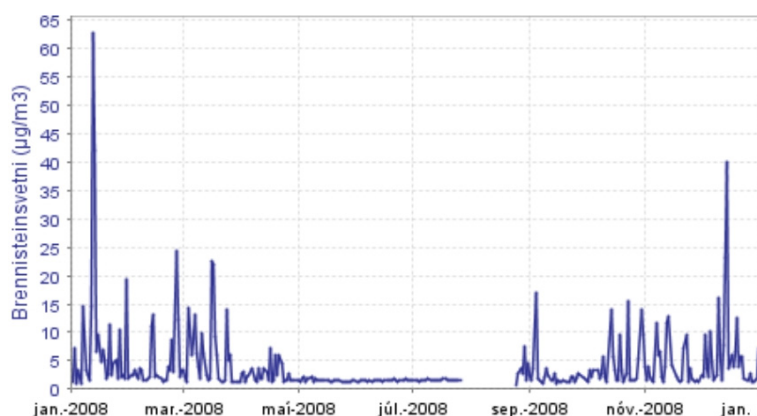
FIGURE 8: H$_2$S concentrations in January-December 2008, averaged over 24-hour periods (Environment Agency of Iceland, 2011)
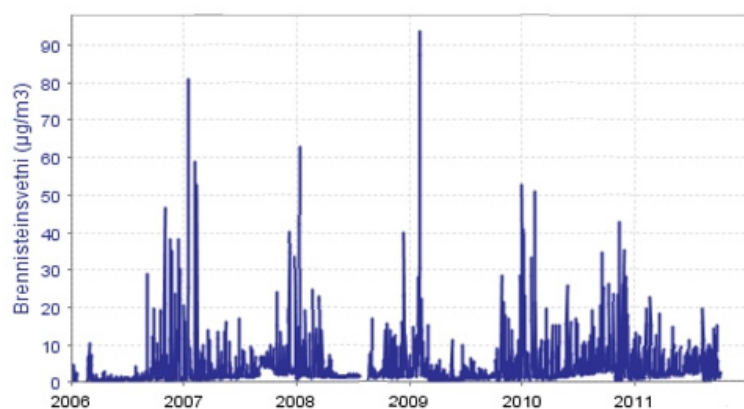

FIGURE 9: H$_2$S concentrations in 2006 – 2011, averaged over 24-hour periods (Environment Agency of Iceland, 2011)

Figure 9 presents the level of H$_2$S concentrations for the entire period from 2006 up to September 2011. In 2010, the total installed capacity of Hellisheidi and Nesjavellir power plants was 213 and 120 MWe, respectively. The number of turbines increased and the monitored concentrations of H$_2$S were raised significantly from the baseline monitoring concentrations (2006). These elevated concentra-tions could affect the H$_2$S concentrations in Reykjavík. The highest concentration in the beginning of each January from 2007-2010 exceeded the Iceland H$_2$S air ambient standard value (50 μg/m^3 averaged over a 24 hour period). The monitoring data showed that the increase of H$_2$S concentrations occurred in the month of January when the chemical was likely to remain for days during winter (WHO, 2003). In June 2010 Iceland introduced a new regulation regarding H$_2$S emissions, establishing a limit for 24-hour mean concentrations at 50 μg/m^3. The regulation becomes legally valid in July 2014.

6.7 Sensitivity and magnitude

A significant impact matrix is an instrument for estimating probability and evaluating substantial emission variables from a proposed study project. The significant potential impact for this study is described based on sensitivity and magnitude. Considering the performance of the H$_2$S dispersion modelling previously approved by international financial institutions (Gilpin, 1995), a systematic approach to evaluating significant impacts was adopted from relevant reports of H$_2$S dispersion modelling in the Ulubelu geothermal area (Boyland et al., 2011).

In accordance with the overall framework, the significance of potential human health impacts was assessed by considering criteria, on the sensitivity of the receptors, developed from baseline information. The sensitivity of the discrete receptors in Reykjavík, Hveragerdi and the vicinity of the power plants, is defined by how close the baseline H$_2$S concentrations are to the Iceland H$_2$S air ambient standard of 50 μg/m^3 averaged over a 24 hour period and 5 μg/m^3 averaged over a year. The WHO guideline of 150 μg/m^3 averaged over a 24 hour period was also taken into account to assess H$_2$S concentrations in relation to internationally recognised health limits. The following categorisation was used to describe sensitivity: high, medium, low, and negligible. The magnitude of the impact was considered from increasing H$_2$S concentrations caused by emissions from the Hellisheidi power plant's future development as a percentage of the Iceland H$_2$S air ambient standard. The resultant total of H$_2$S concentrations was taken from baseline concentrations and also the increase caused by emissions from the Hellisheidi power plant's future development. Subsequent categorisation

identified a range of adverse effects, classified as major, moderate, low or negligible. The descriptions for receptor sensitivity and magnitude are presented in Table 10.

TABLE 10: Description for receptor sensitivity and magnitude

Receptor sensitivity		Impact magnitude	
Definition	Descriptor	Definition	Descriptor
BC>=300% of the standard	High	PC>=75% of the standard	Major
BC>=100% of the standard	Medium	PC>=50% of the standard	Moderate
BC>=75% of the standard	Low	PC>=25% of the standard	Minor
BC<=75% of the standard	Negligible	PC<=25% of the standard	Negligible

Explanation: BC: Baseline Concentration (scenario A); PC: Process Contribution (scenario B)

The significant framework of this study project is presented in Figure 10, in connection with the descriptions in Table 10 for receptor sensitivity and magnitude. Sensitivity and magnitude have then been combined to establish the significance of an impact that can be described by the interaction of the magnitude and sensitivity significance matrix from Hellisheidi power plant's development against the baseline (existing power plant). Any non-negligible increase in excess of Iceland H_2S air ambient standards is regarded as a major effect, and any increases in concentrations above 75 % (percentage) of the H_2S ambient Iceland standard are considered as substantial (Figure 10). In addition, other considerations should be taken into account on assessing the H_2S impact,

FIGURE 10: Significance matrix

where appropriate. In the following section, the significance matrix (sensitivity and magnitude) describes modelling results of emissions from Hellisheidi power plant's future development.

7. MODELING RESULTS

Dispersion modelling was undertaken to determine predicted H_2S concentrations, and to identify periods of excessive air pollution. The baseline and future significant contributions of H_2S concentrations for the project study were established using AERMOD dispersion modelling.

7.1 Results for scenario A

The result of the baseline dispersion modelling predicts elevated H_2S concentrations at identified discrete receptors (Table 8). The identified sensitivity receptors are presented in Table 11 for the highest 24 hour H_2S concentrations. The highest predicted H_2S concentrations were shown by the receptors at Hellisheidi 1 and Hellisheidi 2; these locations are not considered to have a highly significant public health impact as there are only a few workers there over a 24 hour period during a typical week.

TABLE 11: Scenario A (baseline result)

No.	Receptor	PC (µg/m³)	PEC (µg/m³)	PEC as percentage of standard (%)	RS
1	Mosfellsbaer 1	229.05	229.06	458.12	High
2	Mosfellsbaer 2	189.75	189.76	379.52	High
3	Mosfellsbaer 3	37.05	37.06	74.13	Negligible
4	Reykjavík 1	20.68	20.70	41.39	Negligible
5	Reykjavík 2	18.21	18.22	36.45	Negligible
6	Reykjavík 3	21.49	21.50	43.01	Negligible
7	Reykjavík 4	18.56	18.57	37.14	Negligible
8	Reykjavík 5 (Grensásvegur)	16.30	16.31	32.62	Negligible
9	Reykjavík 6	16.50	16.51	33.02	Negligible
10	Reykjavík 7	16.70	16.71	33.42	Negligible
11	Reykjavík 8	16.83	16.85	33.69	Negligible
12	Reykjavík 9	17.00	17.02	34.03	Negligible
13	Reykjavík 10	18.58	18.59	37.19	Negligible
14	Reykjavík 11 (near Lake Ellithavatn)	290.76	290.77	581.55	High
15	Reykjavík 12	103.53	103.54	207.07	Medium
16	Reykjavík 13	267.21	267.22	534.45	High
17	Reykjavík 14	83.25	83.26	166.52	Medium
18	Reykjavík 15	250.63	250.64	501.28	High
19	Reykjavík 16	105.47	105.48	210.96	Medium
20	Reykjavík 17	116.55	116.56	233.12	Medium
21	Reykjavík 18	15.66	15.67	31.35	Negligible
22	Reykjavík 19	15.18	15.19	30.38	Negligible
23	Reykjavík 20	193.67	193.68	387.36	High
24	Reykjavík 21	333.69	333.70	667.39	High
25	Reykjavík 22	237.39	237.40	474.80	High
26	Hafnarfjordur1	20.64	20.65	41.30	Negligible
27	Hafnarfjordur2	15.70	15.71	31.43	Negligible
28	Hafnarfjordur3	14.92	14.93	29.86	Negligible
29	Hafnarfjordur4	16.05	16.06	32.12	Negligible
30	Hafnarfjordur5	75.84	75.85	151.70	Medium
31	Hellisheidi 1	754.64	754.66	1509.31	High
32	Hellisheidi 2	926.35	926.36	1852.72	High
33	Hveragerdi 1	197.78	197.79	395.58	High
34	Hveragerdi 2	183.28	183.30	366.59	High
35	Hveragerdi 3	163.57	163.58	327.17	High
36	Hveragerdi 4	159.90	159.92	319.83	High
37	Hveragerdi 5	156.03	156.04	312.09	High

Notes: Represents the highest 24 hour concentration
PC: Process contribution – the predicted concentration caused by existing Hellisheidi and Nesjavellir power plants (one year's meteorological data);
PEC: Predicted environmental concentration – PC and background air ambient concentrations (see Section 6.4 on scenario description and key input data);
RS: Receptor sensitivity (Table 10).

Numerous discrete receptors predicted elevated H_2S concentrations in the nearest inhabited areas to the power plants: Hveragerdi 1, Hveragerdi 2, Hveragerdi 3, Hveragerdi 4 and Hveragerdi 5. Other discrete receptors showed higher elevated H_2S concentrations in Reykjavík area as follows: Mosfellsbaer 1, Mosfellsbaer 2, Reykjavík 11 (near Lake Ellidavatn), Reykjavík 13, Reykjavík 15, Reykjavík 20, Reykjavík 21 and Reykjavík 22. Here, the concentrations of H_2S were above the WHO

guideline (150 μg/m^3 averaged over a 24 hour period) and Iceland H$_2$S air ambient standard value (50 μg/m^3 averaged over a 24 hour period). Discrete receptors at Reykjavík 12, Reykjavík 14, Reykjavík 16, Reykjavík 17 and Hafnarfjördur 5 area showed smaller H$_2$S concentrations compared to the receptors mentioned above, although the concentrations were still above the Iceland H$_2$S air ambient standard value. The results of the baseline modelling of the maximum 24-hour concentration are presented in Figure 11.
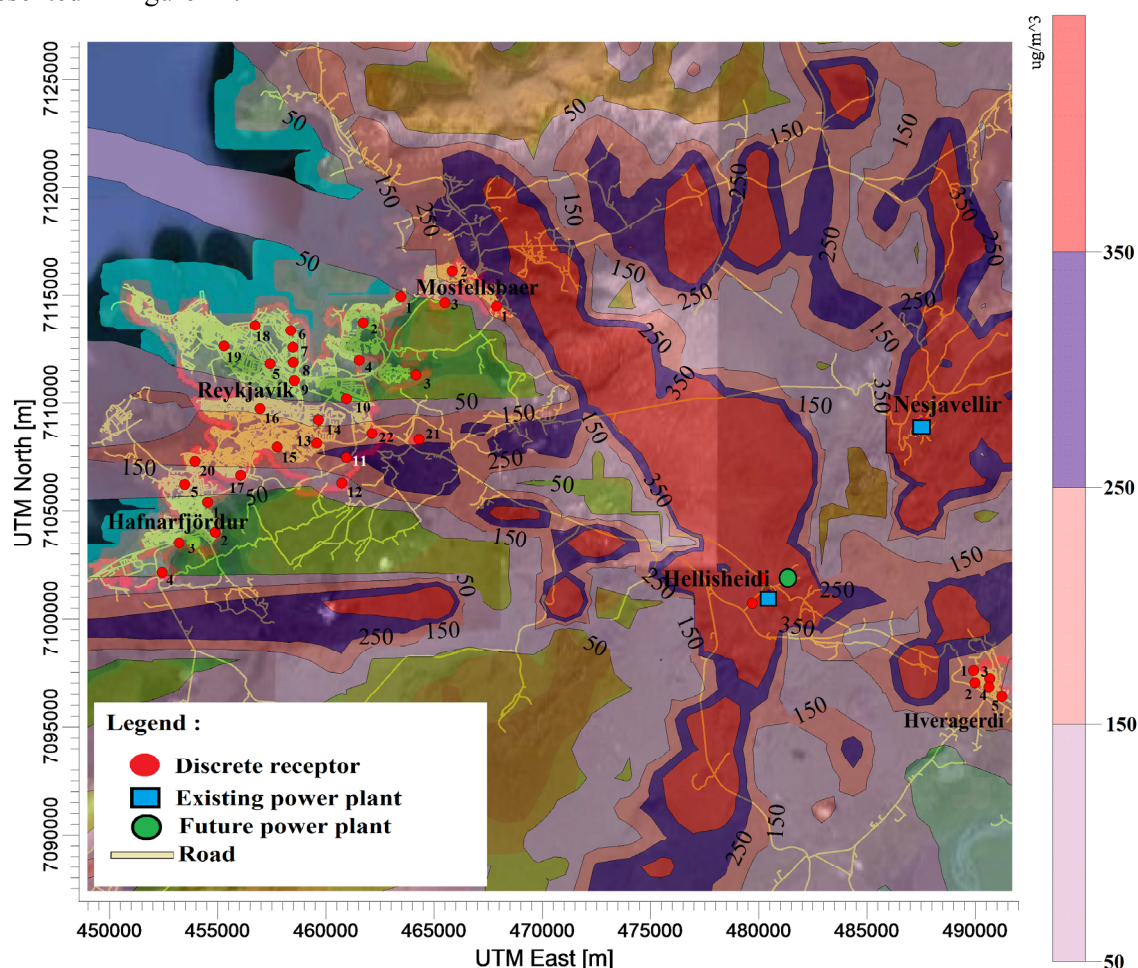
FIGURE 11: H$_2$S modelling results of scenario A

The baseline dispersion modelling results indicated that the air shed had been degraded by the existing power plants of Nesjavellir and Hellisheidi. Several factors influence the dispersal results, including varying emission rates, undulating terrain around the power plant, and the surface roughness of the power facility itself. These factors can create localised instabilities in the atmosphere, resulting in vertical and horizontal variations in pollutant dispersal. Likewise, the geographic location of receptors relative to the power plant and the dominant wind direction can affect modelling simulations; this is partly due to H$_2$S reactions caused by intermediate transport affects, which act to modify the chemistry of the pollutant (Zanetti, 1990). Scenario A was modelled using 12 months of weather observations from the Hellisheidi meteorological station. The simulation showed that elevated H$_2$S concentrations are to be expected at some receptors; this can be explained by a combination of topographic influences and prevailing weather conditions.

The baseline dispersion modelling used one year of meteorological data from 2010 (Ölkelduháls weather station); then it was compared to actual results of H$_2$S data from the continuous monitoring station at Grensásvegur, Reykjavík (Figure 9), which is located approximately 25 km from the emission sources. Both the baseline dispersion modelling and actual H$_2$S continuous monitoring station similarly indicated elevated H$_2$S concentrations, in comparison to the Iceland standard for H$_2$S emissions.

Modelled H_2S concentrations at the existing Hellisheidi and Nesdjavellir power plants are shown in Table 12 in relation to the occupational exposure limit. The modelling results predict concentrations below the occupational standard for 8 hour's exposure time (Ministry of Welfare, 2009).

TABLE 12: Maximum baseline compared to the H_2S occupational standard

Receptor	Averaging period (hour)	PEC ($\mu g/m^3$)	Occupat. standard No. 320/2009 ($\mu g/m^3$)
Hellisheidi existing power plant (1)		7,378	
Hellisheidi existing power plant (2)		7,930	
Hellisheidi existing power plant (3)	8	7,859	14,000
Nesjavellir power plant (1)		6,408	
Nesjavellir power plant (2)		9,252	

Notes: Represents the highest 8 hour concentration
PEC: Predicted environmental concentration

7.2 Results for scenario B

These results present the predicted maximum average 24-hour H_2S concentration contribution due to Hellisheidi power plant's future development, including the existing Hellisheidi and existing Nesjavellir power plants at the identified discrete receptors. The results of Hellisheidi's future development for the highest 24-hour concentrations are presented in Figure 12.
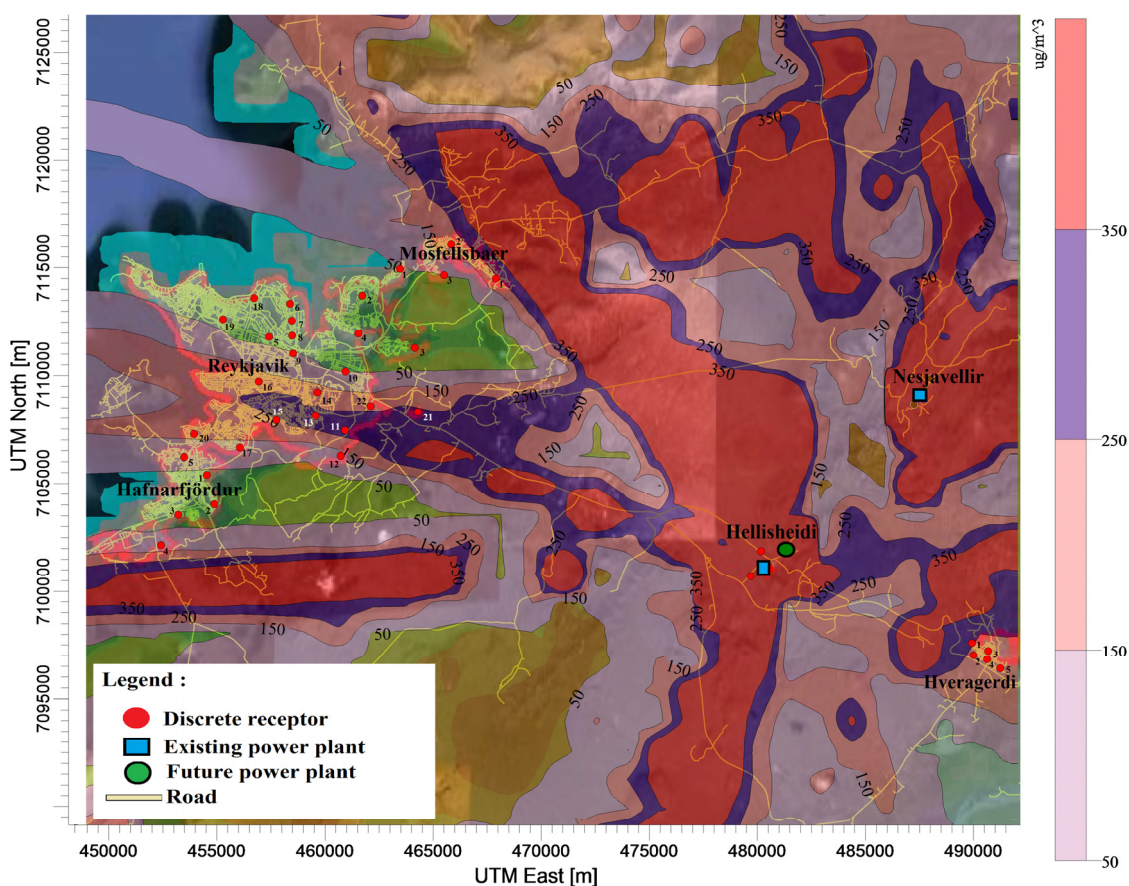

FIGURE 12: H_2S modelling results of scenario B

The highest predicted H_2S concentrations shown nearby are at the receptor at Hellisheidi 1; this receptor has indicated elevated concentrations from the baseline scenario result. However, this receptor is not considered to have a highly significant H_2S public health impact as there are only a few workers there in a 24 hour period during a week.

The modelled concentration values were lower than actual measurements from Hellisheidi 1 receptor. This could be due to recent expansion of power production at site (process contribution) or background concentrations in excess of the assumed baseline. Discrete receptors, which were classified as having 'substantial' impact in Reykjavík, were Reykjavík 11 (near Lake Ellidavatn) and Reykjavík 13. Furthermore, the discrete receptors at Hellisheidi 1, Hveragerdi 1, Hveragerdi 3 and Hveragerdi 4 are near the power plants, located approximately 10 km from the emission sources (Zannetti, 1990) where the maximum ground level impact from an elevated source is generally found. Receptors which were classified as having 'major' impact were Reykjavík 14, Reykjavík 16, Hveragerdi 2 and Hveragerdi 5. The results of the Hellisheidi future development modelling of the highest 24-hour concentrations are presented in Table 13. Another H_2S dispersion modelling of scenario B was undertaken by using one year's worth of meteorological data from Hellisheidi weather station No. 31392. Similar results of the power plant's future development dispersion modelling predicted elevated H_2S concentrations at some identified discrete receptors. Based on the significance matrix, the discrete receptors were classified as having negligible, major, and substantial impacts (Figure 10).

Table 14 presents the number of days that predictions exceed the average 24 hour limit at each of the identified discrete receptors. The result shows that a number of the discrete receptors were classified as 'substantial' and 'major' adverse impact as identified in Tables 11 and 13. During the wintertime, H_2S concentrations remain elevated for longer than during summertime conditions. The predicted number of excess days of 24 hour H_2S may lead to breaches of Iceland's H2S air ambient standard.

The modelling of H_2S dispersion took into account the annual average H_2S concentrations due to the existing Nesjavellir and Hellisheidi power plants, as well as Hellisheidi future development. The results of the dispersion modelling predict elevated H_2S concentrations at identified discrete receptors against the Iceland H_2S ambient standard as presented in Table 15 and Figure 13.

The modelling of occupational exposure during working hours was only considered at the existing Hellisheidi power plant and future Hellisheidi power plant as the power plants (Hellisheidi and Nesjavellir) are at different locations; the distance between them is 1.5 - 9.5 km. The modelling result of 8 hour exposure was predicted to exceed the standard at some receptors at Hellisheidi future power plant (1) and Hellisheidi future power plant (3). The distances of these receptors are a few metres from the emission source (as presented in Table 16). However, workers are exposed to such levels only for short periods. The elevated exposure of H_2S is probably due to building downwash aerodynamics with a distance less than 1 km from the source (Zanetti, 1990) as well as due to terrain and hills around the power plant. Figure 14 summarises dispersal results for the future development of Hellisheidi, based on the highest 8 hour concentrations.

TABLE 13: Scenario B (future development)

Receptor	BC (µg/m³)	PC (µg/m³)	PEC (µg/m³)	Receptor sensitivity*	Change as percentage of standard (%)	Impact magni-tude*	Significance matrix**
Mosfellsbaer 1	229.05	7.36	236.41	High	14.72	Negligible	Negligible
Mosfellsbaer 2	189.75	2.67	192.41	High	5.33	Negligible	Negligible
Mosfellsbaer 3	37.05	2.74	39.79	Negligible	5.48	Negligible	Negligible
Reykjavík 1	20.68	3.95	24.63	Negligible	7.90	Negligible	Negligible
Reykjavík 2	18.21	5.60	23.81	Negligible	11.20	Negligible	Negligible
Reykjavík 3	21.49	5.62	27.11	Negligible	11.24	Negligible	Negligible
Reykjavík 4	18.56	5.75	24.31	Negligible	11.50	Negligible	Negligible
Reykjavík 5 (Grensásvegur)	16.30	5.04	21.34	Negligible	10.07	Negligible	Negligible
Reykjavík 6	16.50	5.08	21.57	Negligible	10.15	Negligible	Negligible
Reykjavík 7	16.70	5.15	21.85	Negligible	10.30	Negligible	Negligible
Reykjavík 8	16.83	5.21	22.04	Negligible	10.41	Negligible	Negligible
Reykjavík 9	17.00	10.53	27.54	Negligible	21.07	Negligible	Negligible
Reykjavík 10	18.58	9.74	28.33	Negligible	19.49	Negligible	Negligible
Reykjavík 11 (near Lake Ellidavatn)	290.76	49.30	340.06	High	98.60	Major	Substantial
Reykjavík 12	103.53	3.83	107.35	Medium	7.66	Negligible	Negligible
Reykjavík 13	267.21	49.40	316.61	High	98.80	Major	Substantial
Reykjavík 14	83.25	97.95	181.20	Medium	195.90	Major	Major
Reykjavík 15	250.63	2.83	253.46	High	5.66	Negligible	Negligible
Reykjavík 16	105.47	107.95	213.41	Medium	215.89	Major	Major
Reykjavík 17	116.55	2.74	119.29	Medium	5.48	Negligible	Negligible
Reykjavík 18	15.66	4.81	20.48	Negligible	9.63	Negligible	Negligible
Reykjavík 19	15.18	4.67	19.85	Negligible	9.35	Negligible	Negligible
Reykjavík 20	193.67	2.61	196.28	High	5.22	Negligible	Negligible
Reykjavík 21	333.69	3.27	336.96	High	6.54	Negligible	Negligible
Reykjavík 22	237.39	3.11	240.50	High	6.21	Negligible	Negligible
Hafnarfjordur1	20.64	2.66	23.30	Negligible	5.32	Negligible	Negligible
Hafnarfjordur2	15.70	4.93	20.63	Negligible	9.85	Negligible	Negligible
Hafnarfjordur3	14.92	4.67	19.59	Negligible	9.34	Negligible	Negligible
Hafnarfjordur4	16.05	50.35	66.39	Negligible	100.69	Major	Negligible
Hafnarfjordur5	75.84	2.59	78.43	Medium	5.19	Negligible	Negligible
Hellisheidi 1	754.64	560.43	1315.07	High	1120.86	Major	Substantial
Hellisheidi 2	926.35	1.61	927.96	High	3.22	Negligible	Negligible
Hveragerdi 1	197.78	54.34	252.12	High	108.69	Major	Substantial
Hveragerdi 2	183.28	34.96	218.25	High	69.92	Moderate	Major
Hveragerdi 3	163.57	45.34	208.91	High	90.67	Major	Substantial
Hveragerdi 4	159.90	40.62	200.53	High	81.25	Major	Substantial
Hveragerdi 5	156.03	31.23	187.26	High	62.46	Moderate	Major

Notes: Represents the 1st maximum 24 hour concentration;
BC: Baseline Concentration (scenario A);
PC: Process Contribution (scenario B) – the predicted concentration caused by Hellisheidi power
   plant future development (1 year meteorological data);
PEC: Predicted environmental concentration; PC and BC;
* See Table 10;
** See Figure 10.

TABLE 14: Number of days on which the 24 hour H_2S ambient standard is exceeded

No.	Receptor	Number of times 24 hour H_2S ambient standard is exceeded (day)	No.	Receptor	Number of times 24 hour H_2S ambient standard is exceeded (day)
1	Mosfellsbaer 1	4	11	Reykjavík 21	2
2	Mosfellsbaer 2	3	12	Reykjavík 22	2
3	Reykjavík 11 (near Lake Ellidavatn)	2	13	Hafnarfjordur4	1
4	Reykjavík 12	1	14	Hafnarfjordur5	1
5	Reykjavík 13	2	15	Hveragerdi 1	3
6	Reykjavík 14	2	16	Hveragerdi 2	3
7	Reykjavík 15	2	17	Hveragerdi 3	3
8	Reykjavík 16	1	18	Hveragerdi 4	3
9	Reykjavík 17	1	19	Hveragerdi 5	3
10	Reykjavík 20	1			
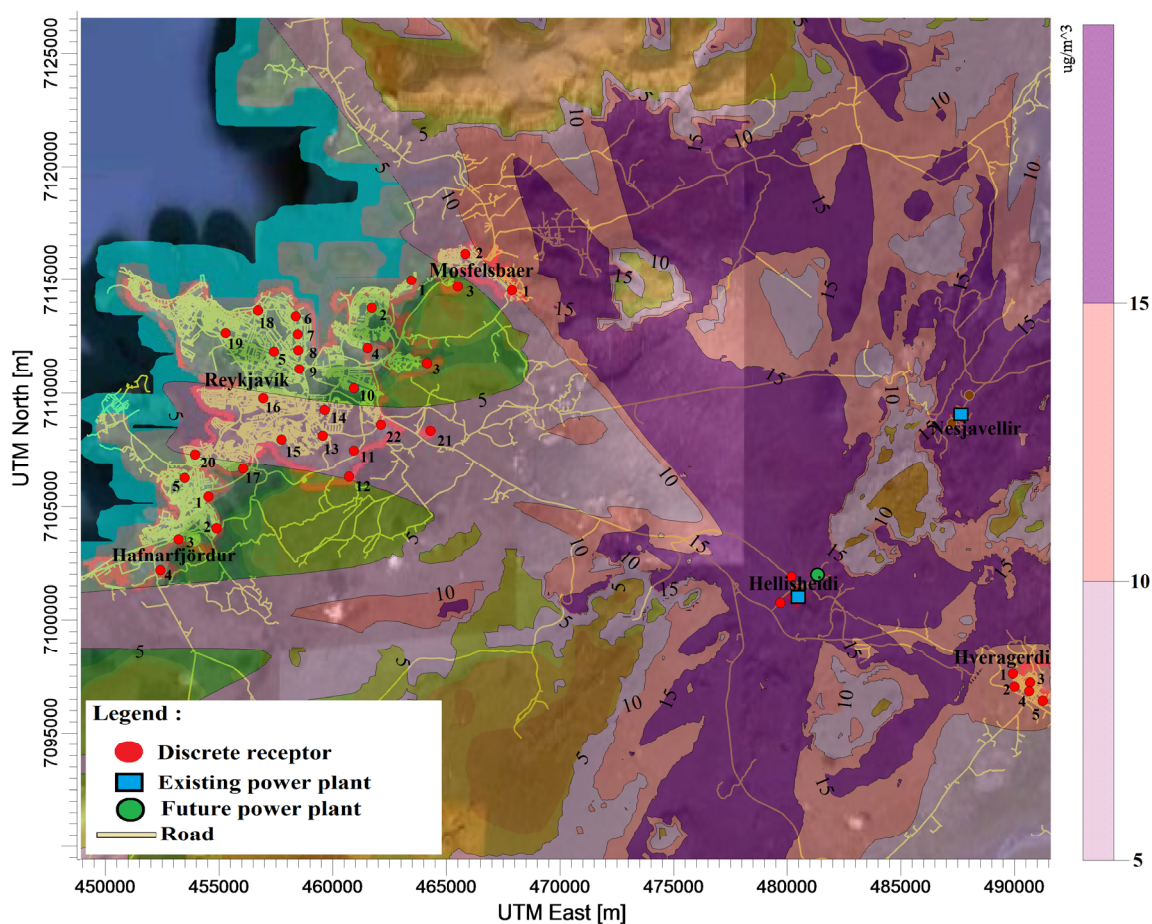
FIGURE 13: Annual H_2S modelling result

TABLE 15: Scenario B (annual predicted H$_2$S concentration)

No.	Receptor	Predicted annual average H$_2$S concentration (µg/m^3)	No.	Receptor	Predicted annual average H$_2$S concentration (µg/m^3)	(*)Annual Air Ambient Standard No. 514/2010 (µg/m^3)
1	Reykjavík 20	5.07	9	Reykjavík 13	9.18	5
2	Reykjavík 12	5.27	10	Reykjavík 11 (near Lake Ellidavatn)	9.36	5
3	Reykjavík 16	5.46	11	Mosfellsbaer 1	10.01	5
4	Reykjavík 14	5.97	12	Hveragerdi 5	10.52	5
5	Mosfellsbaer 2	7.63	13	Hveragerdi 3	11.05	5
6	Reykjavík 22	7.70	14	Hveragerdi 4	11.20	5
7	Reykjavík 15	7.98	15	Hveragerdi 1	12.06	5
8	Reykjavík 21	8.37	16	Hveragerdi 2	12.10	5

Note: (*) refers to Table 1

TABLE 16: Maximum 8 hour averages compared to the H$_2$S occupational standard
(due to Hellisheidi future development)

Receptor	Averaging period (hour)	PEC (µg/m^3)	Occupational Standard No. 320/2009 (µg/m^3)
Hellisheidi existing power plant (1)	8	7,381	14,000
Hellisheidi existing power plant (2)		7,984	
Hellisheidi existing power plant (3)		7860	
Hellisheidi future power plant (1)		38,269	
Hellisheidi future power plant (2)		10,324	
Hellisheidi future power plant (3)		179,988	
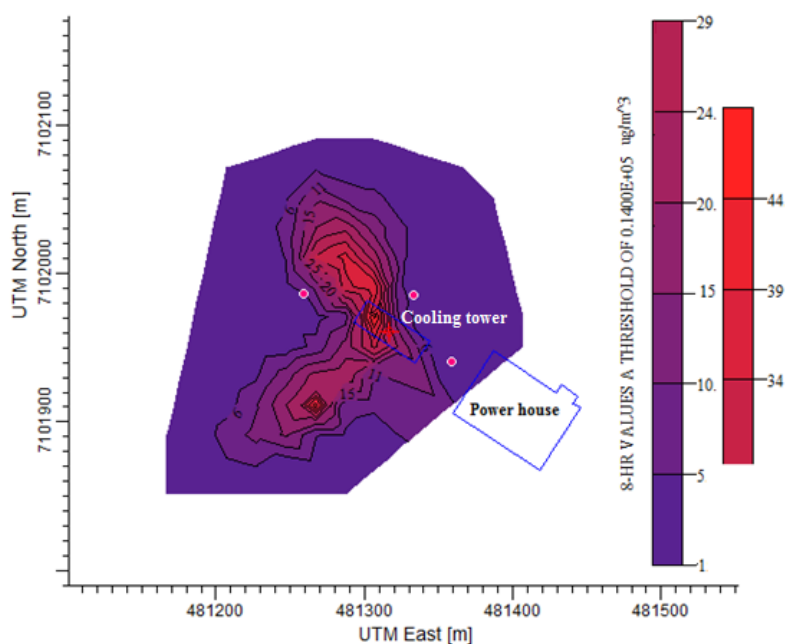
FIGURE 14: H$_2$S modelling results of occupational
exposure (Hellisheidi future development)

8. DISCUSSION - REVIEW OF HEALTH EFFECTS

8.1 Health effect review

Studies of the health effects of H_2S on the population in the Reykjavík area have not been published in the peer review literature. However, there exist two master studies from the University of Iceland on air pollution (including H_2S) and drug use for respiratory and cardiovascular diseases, which will not be discussed in this report (Carlsen, 2009; Finnbjörnsdóttir, 2010). Never-theless, there are numbers of internationally published studies on possible long term adverse health effects of H_2S, solely and in combination with some other pollutants. In the following section, a description of some of the epidemiological studies in relation to adverse health effects of H_2S exposure will be given, as the acute toxicological effects have already been reviewed in Section 4.2. This overview will also be mainly confined to H_2S emissions from geothermal power plants and active thermal areas.

Ecological epidemiological studies have been conducted on the population of an active geothermal area at Rotorua, New Zealand. In the city of Rotorua, geothermal energy is used in industry and for heating purposes, and H_2S is also emitted directly from the ground of the active thermal areas. In a study of the residents in Rotorua, the mortality for selected diseases was compared to the rest of New Zealand. Monitoring in the 1970s revealed levels of H_2S as high as 1 mg/m^3; the median concentration was 30 μg/m^3 with 35% of the measurements over 70 μg/m^3 and 10% over 400 μg/m^3. Mortality data on the respiratory system showed a significantly elevated standardized mortality ratio (SMR = 1.18; P < 0.001) (Bates et al., 1997). Adjustment analysis for ethnicity were carried out as population in the Rotorua area has markedly more Maori than the population in the rest of New Zealand and also disease and mortality rates are relatively higher in the Maori population than in the non-Maori population. When the data were stratified by sex and ethnicity, female Maoris had an SMR of 1.61 (P = 0.001). However, the authors indicated that the prevalence of smoking was not evaluated as a potential confounder and that there may also have been some misclassification of study subjects with regard to ethnicity (Bates et al., 1997). In a cancer incidence study of the same authors on the population in Rotorua, an elevated rate for nasal cancers was found as well as an increase in lung cancer among the Maori women (SIR = 1.48; P = 0.02), and this was not explained by higher smoking rates. However, the study did not permit firm conclusions because of a lack of exposure measurements (Bates et al., 1998). In still another study from Rotorua, the emissions of hydrogen sulphide (H_2S) and carbon dioxide (CO_2) were investigated. Buildings constructed in the gas anomaly area were selected for the study. Eight of the nine buildings studied were found to suffer problems with soil gases entering the indoor air through the structure. The primary means of gas entry was directly from the ground through the floors, walls, and subsurface pipes. Indoor vents were located and found to be emitting up to ~200 ppm H_2S and ~15% CO_2, concentrations high enough to present an acute respiratory hazard to persons close to the vent (e.g., children playing at floor level). It was clear that potential or real health hazards may exist in some buildings affected by ground gas emission (Durand and Scott, 2004).

The available human data on chronic exposure to low-level concentrations of H_2S in the literature is scarce. However, a study was conducted on Canadian residents living downwind from two natural gas refineries at Pitcher Creek, because of concerns about health hazards associated with chronic low-level exposure to H_2S (Schechter et al., 1989). The results of this study did not indicate any increase in cancer incidence (Schechter et al., 1989).

In the previously mentioned study from Rotorua (Bates et al., 1998) some elevated rates of disease of the nervous system and eye were found in hospital discharge data, however the authors concluded that it was not possible to state firmly whether these findings were attributable to the H_2S exposure as the results might be confounded by simultaneous exposure to mercury (Bates et al., 1998). More recent studies from Rotorua have, however, strengthened the suggestions that there are chronic health hazards from low-levels H_2S exposure concerning nervous system diseases (Bates et al., 2002), cardiovasculatory diseases (Bates et al., 2002), and respiratory diseases (Durant et al., 2006; Bates et

al., 2002). A study of emission combinations from geothermal sources and automobiles was conducted in a residential area of Northwest Taipei. This study intended to evaluate geothermal emitted acid aerosol and H_2S pollution from geothermal area and hot springs. The H_2S concentration was 1705 ppb in the geothermal area with low traffic density and the mean concentration was 404.06 ppb; this number was higher than the WHO guideline and might cause eye irritation. The result indicated geothermal emissions, automobile emissions, and secondary acid aerosols generated via photochemical reactions all contribute to Taipei urban air pollution. For a long-term period, geothermal emissions, automobile emissions and photochemical reactions may increase health risks for residents, such as nervous system and respiratory diseases (Lin et al., 2010).

8.2 Mitigation

The H_2S dispersion modelling results indicated elevated H_2S concentrations at some discrete receptors in Reykjavík and Hveragerdi. Mitigation measures are an important factor in avoiding, reducing and, if possible, remedying any significant adverse effect of H_2S emission from Nesjavellir and Hellisheidi power plants to comply with the standard.

In accordance with the Iceland H_2S air ambient standard, appropriate abatement technology is required to capture H_2S from NCGs. The H_2S impact can be reduced by encouraging greater atmospheric dispersion and the dilution of emissions using appropriate technology of H_2S emission reduction. For instance, greater dispersal could be achieved by changing structural designs at the power stations (Wydeven, 2010). The effectiveness of mitigation should be assessed in terms of the extent to which the problem will be reduced as well as the cost of implementation (Morris and Therivel, 1995).

Given the nature of the potential public health effects, the design of a H_2S monitoring system is required, particularly near densely populated areas and locations which indicated high levels of H_2S concentrations. A H_2S emergency preparedness plan involving community exposure, government and power producer is needed in the event to respond to elevated levels of H_2S concentrations and or other emergency conditions. In addition, mitigation measures directed to workers dealing with H_2S exposure are as follows: proper training on H_2S basic knowledge, hazards, exposure, confined space and respiratory system; appropriate procedures of safety-health and emergency; engineering controls; providing H_2S monitoring equipment or detection (personal H_2S detection or self-contained breathing apparatus (SCBA), particularly with H_2S exposure to 50 ppm which is considered immediately dangerous to life and health (Rom, 1998).

9. CONCLUSIONS AND RECOMMENDATIONS

H_2S dispersion modelling of 8 hour, 24 hour and annual averaging periods was undertaken to assess the impacts on receptors at representative locations in Reykjavík, Hafnarfjördur, Mosfellsbaer and Hveragerdi. Two scenarios (Scenario A-baseline and Scenario B-future development) were assessed and compared with the national standard (Iceland H_2S air ambient standard and occupational standard) and the WHO air quality guidelines. All prerequisite factors for running AERMOD were available, selected, and used. The model predicted elevated concentrations due to H_2S emission from the power plants; the model predicted higher concentrations of H_2S due to increased emissions from the future development of the power plant (increase from Scenario A to Scenario B). The environmental impact at several discrete receptors were classified from negligible to substantial; according to the existing power plants, the model predicted similar results (Scenario A) as have been obtained from the continuous monitoring station (Grensásvegur); in order to comply with the standard, appropriate mitigation through technology abatement is required for reducing any significant adverse effects and to prevent a public health risk of H_2S concentration exposure to the community. H_2S dispersion modelling is a unique tool for evaluating emission control in order to minimize environmental impacts

for short-term control and long-term control and can be used very effectively in the design of a definitive monitoring network.

Recommendations of H_2S dispersion modelling: examine the trends and behaviours in the dataset of H_2S concentrations to assist in understanding what might be influencing the air quality (daily, day of week, monthly average, monthly maximum, and long term benchmark concentration trends for H_2S pollutants); a study of the variants of meteorological fluctuation, particularly for the range of worst-case meteorological data, is required to demonstrate the fluctuation of H_2S concentrations. It is recommended that additional dispersion modelling be undertaken once power plant capacity has been increased, taking into consideration long-term predictions on social, economic, public health and power plant strategy; to conduct risk assessments of possible health impacts due to community exposure to H_2S; monitoring should be continued in order to assess the effectiveness of any mitigation measures proposed and to ensure that any potential problems identified have been minimized or eliminated.

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