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Study of the impact of the waste-to-energy plant on the concentration of selected heavy metals in the air of the broader location of the chemical industry complex in Prahovo

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1. INTRODUCTION

The purpose of this study is to provide a representative assessment of the impact of the waste-to-energy plant on the concentration of certain heavy metals (Pb, As, Ni, and Cd) in ambient air of the broader location of the chemical industry complex in Prahovo. The assessment is based on the use of a computer-based dispersion model for the calculation of ground concentrations of pollutants in the area under consideration. To give a qualitative assessment of the contribution to the existing state of air quality, the results obtained by the mentioned model should be compared with the relevant national and international objectives for air quality, i.e. *The Decree on the conditions for monitoring and air quality requirements ("Official Gazette of the Republic of Serbia", No. 11/10, 75/10 and 63/13)* and *Directive (EU) 2024/2881 of the European Parliament and of the Council of 23 October 2024 on ambient air quality and cleaner air for Europe (recast).*

For the purposes of this study, the modeling was performed with the AERMOD software package using appropriate input parameters.

This Study considered the boiler plant emitter of the Waste-to-Energy plant, for which emission limit values for two summable groups of heavy metals were prescribed in *Commission Implementing Decision (EU) 2019/2010 of 12 November 2019 establishing the best available techniques (BAT) conclusions, under Directive 2010/75/EU of the European Parliament and of the Council, for waste incineration (notified under document C(2019) 7987).* The first group consists of a summable of Cd and Tl, and the second Sb, As, Pb, Cr, Co, Cu, Mn, Ni, V. Processing and physical characteristics of the emitter were provided by the Contracting Authority of the Study.

Given that the aim of air quality modeling, within this Study, is to provide a representative assessment of the impact of the facility in question on air quality in the considered model domain, other sources that do not belong to the chemical industry complex were not taken into account, nor was background pollution included in the presented modeling results.

The results of the modeling, for the considered pollutant model, are graphically presented through spatial distributions of ground-level concentrations (isopleths) as maximum values obtained by the appropriate time periods of averaging.

2. MODEL DESCRIPTION

2.1 Models of pollutants spreading through the air

The concentration of a pollutant in a specific point or area depends on numerous variables, which include, among other things, emission values, distance from the source of pollution, as well as meteorological conditions.

To create the possibility of taking adequate preventive, spatial planning, and environmental measures to protect the air from excessive pollution, a system for monitoring air quality should be provided, to obtain a precise image of air pollution on the territory of the observed area. In situations where there is no air quality measurement data from the field (at the design phase of new industrial facilities), mathematical modeling is used, that is, the simulation of processes in the atmosphere with the help of mathematical models. Atmospheric dispersion models of pollutants are used to determine the decrease in the concentration of pollutants in flue gas during the removal of the smoke plume from the source of emissions, and also to estimate their ground concentrations.

The dispersion model represents the mathematical expression of the influence of atmospheric processes on pollutants in the atmosphere. Atmospheric conditions (which include wind speed and direction, air temperature, and mixing height) are simulated using dispersion models, and pollutant concentrations are estimated as they move away from the emitter. With the inclusion of atmospheric chemistry, these models can also generate estimated values of the concentration of pollutants produced in secondary reactions. Dispersion models can be used in assessment cases when determining the negative impact of a new source of pollution in an area, as well as in cases where the air quality can be positively influenced by the application of some measures. Therefore, dispersion models are used when it is necessary to give an estimate of the concentration of pollutants in the ambient air to assess the impact of a new emitter or in cases of verification of the implementation of mitigation measures on existing facilities. Existing dispersion models vary in complexity. For most models, as minimum input data, it is necessary to provide meteorological data, data on emissions, as well as certain data on the emitter (stack height, flue gas velocity in the emitter, etc.). For some more complex dispersion models, it is necessary to provide data on the topography of the terrain, more detailed data on pollutants as well as data on the characteristics of the soil in the model domain. As a result of the use of these models, the concentrations of the considered pollutants in a certain area are obtained, which is of interest for the assessment of ambient air quality and depends on the type of model used.
The models are more reliable for estimating average concentrations over longer periods than over shorter ones, for a specific location. They are reasonably reliable for estimating the value of the highest pollutant concentration that occurs somewhere at some time within the observed area. In general, modeling requires three types of information:

- on the source of emissions,
- on the meteorology of the area under observation, and
- about receptors (terrain characteristics).

2.2 Gaussian dispersion models

In methodological research and practice, Gaussian diffusion models are most often encountered. First of all, it should be stressed that this Gaussian model is quite empirical. These are the models that are most often applied in practice. The main reasons in favor of the application of these models are, first of all, the simplicity of their application as well as a relatively good match with physical experiments. Gaussian models are based on the assumption that the distribution of the concentration of a passive substance in the smoke plume has a certain mathematical form, so they contain the Gaussian diffusion equation, which, represents the solution of Fick's diffusion equation with constant coefficients. The basis of the Gaussian model of the smoke plume is the following equation:

$$C(x,y,z)=\frac{Q}{2\pi u\sigma_y\sigma_z}\exp\left(-\frac{y^2}{2\sigma_y^2}\right)\left\{\exp\left(-\frac{\left(z-H^2\right)}{2\sigma_z^2}\right)+\exp\left(-\frac{\left(z+H^2\right)}{2\sigma_z^2}\right)\right\}$$

Where:

$C(x,y,z)$	- Pollutant concentration at point (x,y,z) $\left[g/m^3\right]$
Q	- Mass flow of the pollutant at the emitter $\left[g/s\right]$
u	- Wind speed $\left[m/s\right]$
σ_y,σ_z	- Standard deviations of the smoke plume cross section $\left[m\right]$
H	- Effective stack height $\left[m\right]$
x	- Distance from the source, in the direction of the wind $\left[m\right]$
y	- Horizontal distance from the centerline of the smoke plume $\left[m\right]$
z	- Distance from the ground $\left[m\right]$

Figure 2.1 shows a schematic representation for an easier understanding of the principles on which Gaussian models function, i.e. the coordinate system used in them. In these models, the discharge itself, i.e. the emitter is assumed to be the coordinate origin, while the calculation of the concentration and the spread of the smoke plume is observed in the *x*, *y*, and *z* directions.

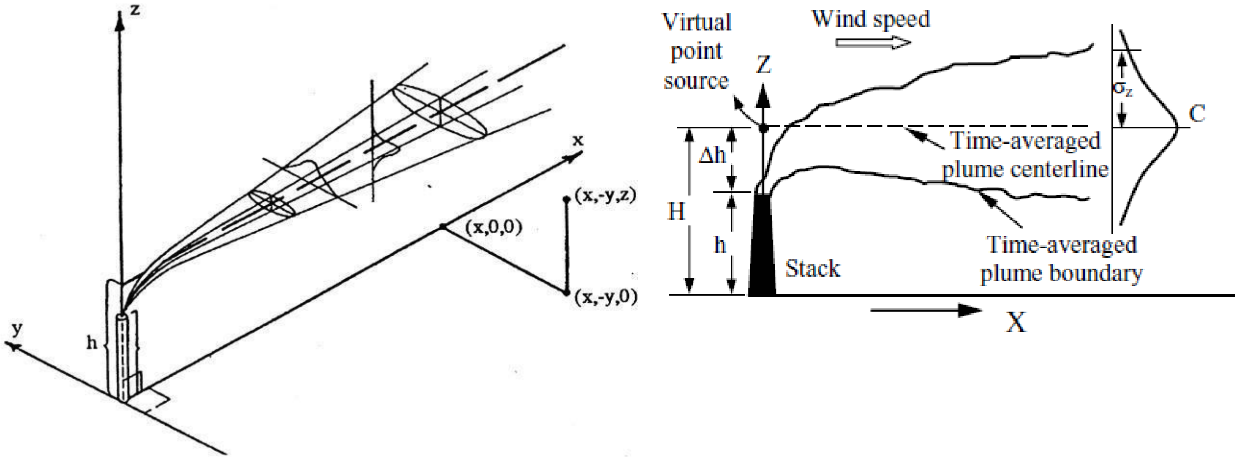


Figure 2.1 Layout of the coordinate system with Gaussian distribution in horizontal and vertical directions

H is the effective height of the stack (taking into account the additional height Δh, to which the smoke plume rises above the physical height of the stack h, i.e. $H = h + \Delta h$), while σ_y and σ_z are parameters of the normal distribution in the y and z directions, i.e. dispersion coefficients in y and z directions.

The Gaussian equation implies that the smoke plume spreads according to the Gaussian distribution principle in the horizontal and vertical planes. The standard deviation of the distribution of pollutant concentrations in the smoke plume in the horizontal (transverse) plane is denoted by *sigma y* (σ_y) and the corresponding distribution of concentration in the vertical plane is denoted by *sigma z* (σ_z). As already noted, these are called dispersion or diffusion coefficients. The values of the diffusion coefficients vary depending on the height above the ground, roughness of the ground, wind speed, and distance from the emitter. The values of the diffusion coefficients are usually determined based on the stability classes of the atmosphere.

The model introduces the following assumptions:
1. Emission value is constant;
2. Dispersion (diffusion) in the direction (x) of the wind is negligible;
3. Meteorological conditions in the horizontal plane are constant throughout the model domain. For each modeled hour:
   a. The average value of wind speed is used.
   b. The wind direction is constant.
   c. The temperature is constant.
   d. The atmospheric stability class of the atmosphere is constant.
   e. The mixing height is constant.
4. There is no change in the vertical gradient of the wind speed.
5. The characteristics of the smoke plume are finite (the smoke plume is independent for each hour, and values originating from the previous hour do not affect its characteristics).

6. Pollutants are considered as inert gases or aerosols that remain suspended in the air and follow turbulent atmospheric movements.
7. Dispersion in the transverse (*y* direction) and vertical (*z* direction) takes place in the form of a Gaussian distribution around the center line of the smoke plume.

2.3 Description of the model used in the Study

To analyze the impact of the waste pretreatment filter system and activated carbon filter within the waste-to-energy plant on the air quality of the wider location of the chemical industry complex in Prahovo, the software package AERMOD was used, i.e. a model based on the Gaussian distribution and recommended by the EPA (U.S. Environmental Protection Agency). AERMOD includes a wide range of capabilities for modeling the impact of pollutants on air pollution. The mentioned model provides the possibility of modeling a number of pollution sources, including point, line, surface, and volume sources. The model contains algorithms for the analysis of aerodynamic flow in the vicinity of and around buildings (*building downwash*). The values of emissions of polluting substances from the source can be treated as constant during the analysis period, or they can vary during the month, the observed period, the hour or some optional time of occurrence of changes.

The results shown in this study were achieved using a model that included emissions of two summable groups of heavy metals (Cd and Tl, i.e. Sb, As, Pb, Cr, Co, Cu, Mn, Ni, and V), which are emitted from a point emitter, i.e. a stack of the boiler plant for the Waste-to-energy plant. During modeling, other emission sources outside the chemical industry complex were not considered, nor was background pollution included.

AERMOD is a stationary plume model, which starts from the assumption that in a stable boundary layer, the concentration of pollutants in both vertical and horizontal directions can be described by a Gaussian distribution. In the convective boundary layer, in the horizontal direction, it is assumed that the concentration of the pollutant takes a Gaussian distribution, while the vertical distribution is described with a bi-Gaussian probability density function. Additionally, AERMOD considers "plum-lofting" in the convective boundary layer, where part of the smoke plume mass, released from the lift source, rises and remains near the top of the boundary layer before mixing in the convective boundary layer. AERMOD also tracks any smoke plume mass that penetrates the elevated stable layer and then allows it to repenetrate the boundary layer when and if possible.

Figure 2.2 shows the information flow and processing in the AERMOD software package. The model consists of a main program (AERMOD) and two pre-processors (AERMET and AERMAP).

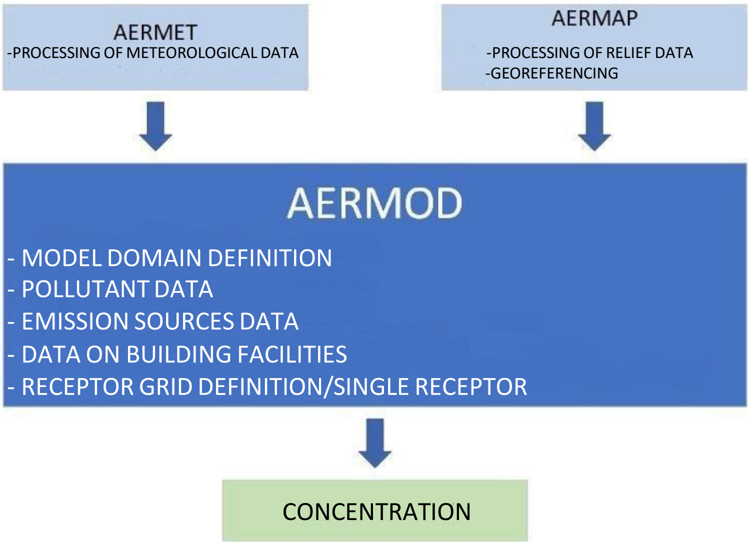


Figure 2.2 Information flow and processing in the AERMOD software package

The main purpose of the AERMET pre-processor is to determine, based on representative meteorological measurements on the model domain, the boundary layer parameters that are used to estimate the wind, turbulence, and temperature profiles for the model's needs. The parameters of the surface layer provided by AERMET are Monin-Obukhov length, surface friction velocity, surface roughness, surface heat flux, and convection velocity. AERMET also provides estimates of convective and mechanical mixed layer heights.

Although AERMOD has the ability to estimate meteorological profiles with measurement data from only one height, it will use as much data as the user can provide to define the vertical boundary layer structure.

As it is very difficult to represent the real terrain as a set of idealized terrain features and associate it with each receptor, AERMAP (terrain pre-processor for AERMOD), operates from the receptor's point of view and takes into account the terrain features around each receptor to objectively determine the representative terrain height associated with a specific receptor. The AERMAP terrain pre-processor uses terrain data to calculate terrain height effects. The terrain height is uniquely defined for each receptor at a site and is used to calculate the streamline height. The data grid required for AERMAP is obtained from the DEM model (Digital Elevation Model). AERMAP is also used to create the receptor grid. Through AERMAP, an altitude is automatically assigned to each receptor. AERMAP defines the input data for each receptor to AERMOD: the location of the receptor, its elevation, and the specific elevation scale of the receptor's terrain.

The emission modeling procedure included the following stages:
1. Creation of plant plan, including sources and facilities;
2. Defining the domain of the model and the location of the receptor;

3. Creation of emission inventory of all monitored emitters;
4. Characterization of the type of sources;
5. Entry and analysis of data on buildings;
6. Processing necessary meteorological data;
7. Processing of terrain data;
8. Modeling and analysis of results.

2.4 Terrain data

AERMOD includes significant flexibility in specifying receptor location. The user has the possibility of specifying a complex grid of receptors in the analysis, where a combination of *Cartesian* and polar receptor grids is also possible. During modeling, AERMOD takes into account the topography of the terrain as well as the height of the receptors in relation to the existing terrain. Terrain elevation data is key to characterizing the variability of terrain, sources, buildings, and receptor elevations in the model domain. Terrain elevations affect emissions concentrations by moving the bisector of the plume closer to or farther from the receptor. Computer models accept a digital data file from which elevation data can be interpolated. During model development, Digital Elevation Model (DEM) data was entered into AERMOD, which assigned elevations to receptors, sources, and buildings.
During modeling for the needs of this Study, NASA digital maps SRTM1 - Shuttle Radar Topography Mission (resolution ~30m, 1 arc-sec) processed by AERMAP were used (Figure 2.3).

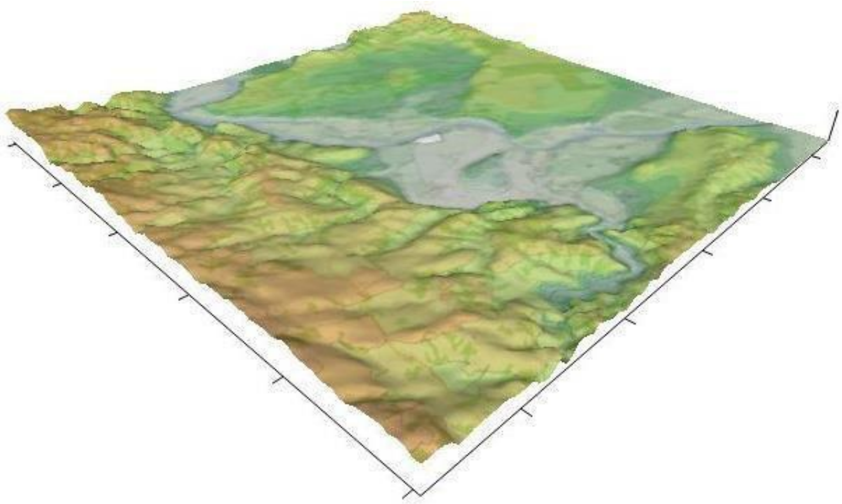


Figure 2.3 Overview of Processed 3D Model Domain Terrain

It was necessary to define terrain elevations, as well as locations and intervals between receptors and facilities based on the Universal Transverse Mercator – UTM coordinate system. Receptors are usually positioned on a coordinate grid (grid), as well as on some specific locations (*discrete*). A grid of receptors covers a large area, while individual receptors can be defined as objects of special interest (e.g. a school, hospital, or nearest neighboring property).

The modeling for the purposes of this study covered an impact zone of 50 km x 50 km, that is, an area of 2500 km^2 (Figure 2.4). When creating the model, a **Cartesian coordinate system was used with a variable distance (Multi-Tier Grid)** between adjacent points (receptors), as follows:

20 m…at a distance of up to 3000 m from the emitter,
100 m…at a distance of up to 5000 m from the emitter,
250 m…at a distance of up to 10000 m from the emitter,
1000 m…at a distance of up to 25000 m from the emitter,

which makes a total of 104121 receptors, which are defined by x and y coordinates expressed in meters and in the Cartesian coordinate system.

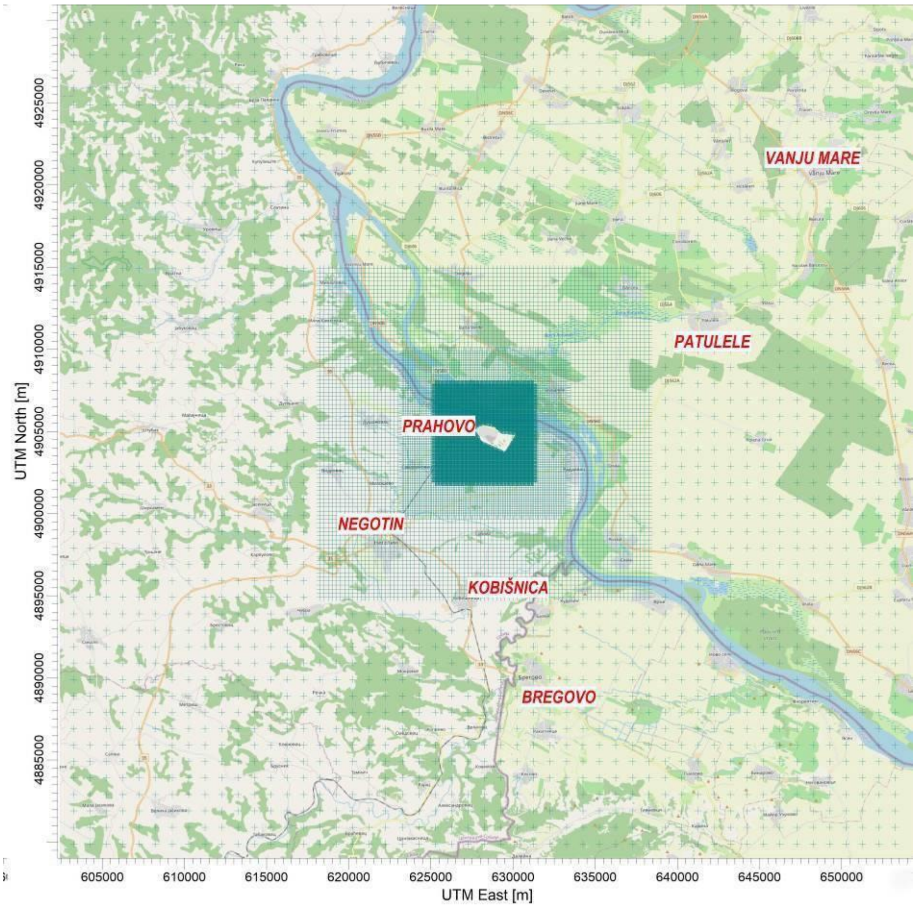


Figure 2.4 Display of 2D model domain terrain and UTM coordinate system

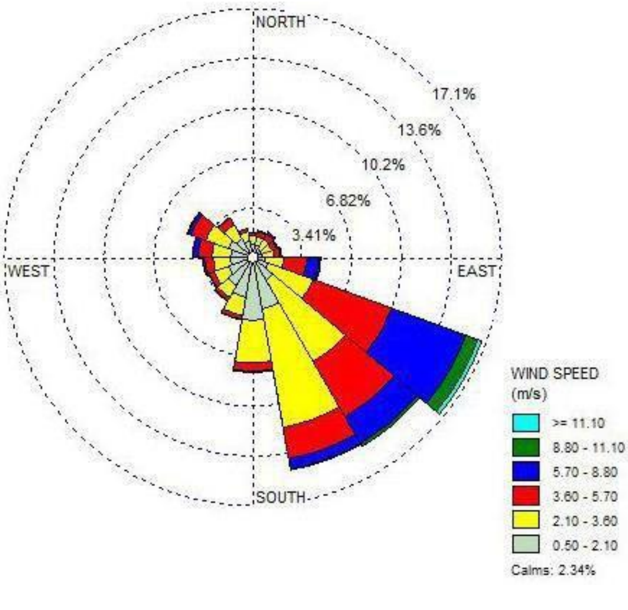
2.5 Meteorological data

AERMET, a meteorological pre-processor, prepares hourly values of surface and upper atmosphere data for use in AERMOD. The input data in AERMET are data on surface observations of hourly values of surface-level parameters, which include, among others, wind speed, temperature, and cloudiness, while a file containing data on the upper layers of the atmosphere provides information on the vertical structure of the atmosphere. This includes layer height, pressure, temperature, and relative humidity.

Meteorological data used for the preparation of this Study include hourly values of the following parameters:

- Wind speed,
- Wind direction,
- Air temperature,
- Relative air humidity,
- Atmospheric pressure,
- Cloudiness.

To define local prevailing meteorological parameters, WRF-MMIF hourly meteorological data for a specific location (Prahovo Chemical Complex) and a period of five consecutive calendar years (from 2017 to 2021) were acquired from the company *Lakes Environmental Consultants* from Canada. This data set consists of information about the surface and upper layers of the atmosphere, which are needed to run the dispersion model. Figures 2.5-2.10 show the wind rose analysis (wind blowing direction) and the wind blowing frequency analysis, based on meteorological data for the period 2017-2021.



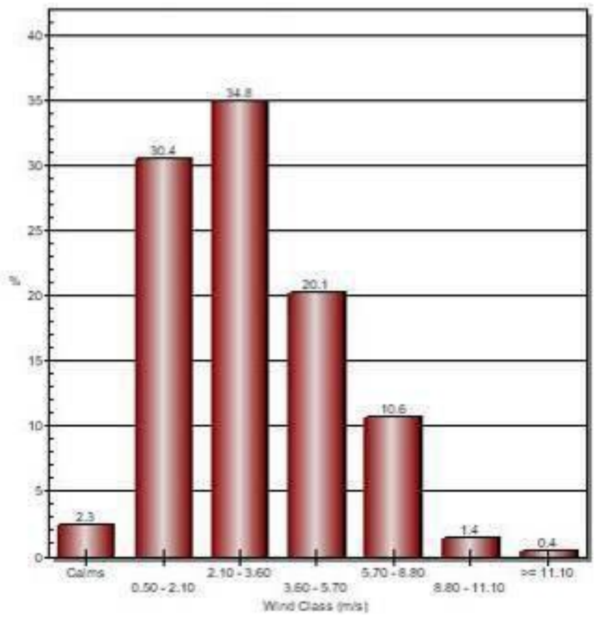


Figure 2.5 Wind rose and frequency chart for 2017-2021

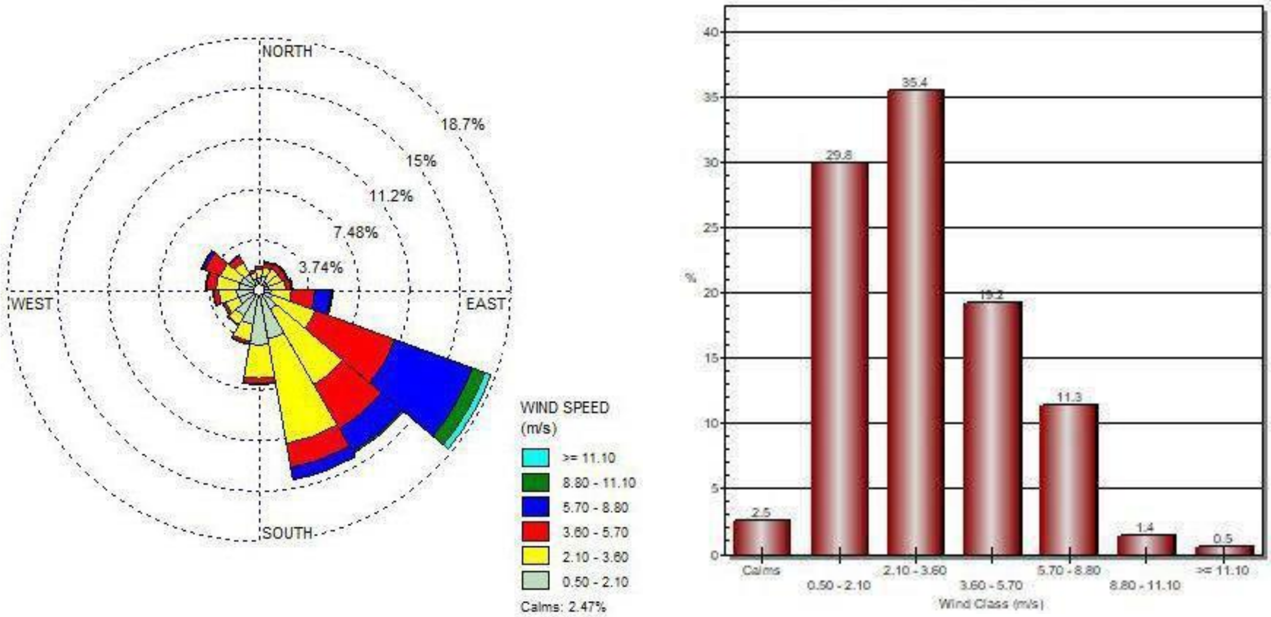


Figure 2.6 Wind rose and frequency chart for 2017

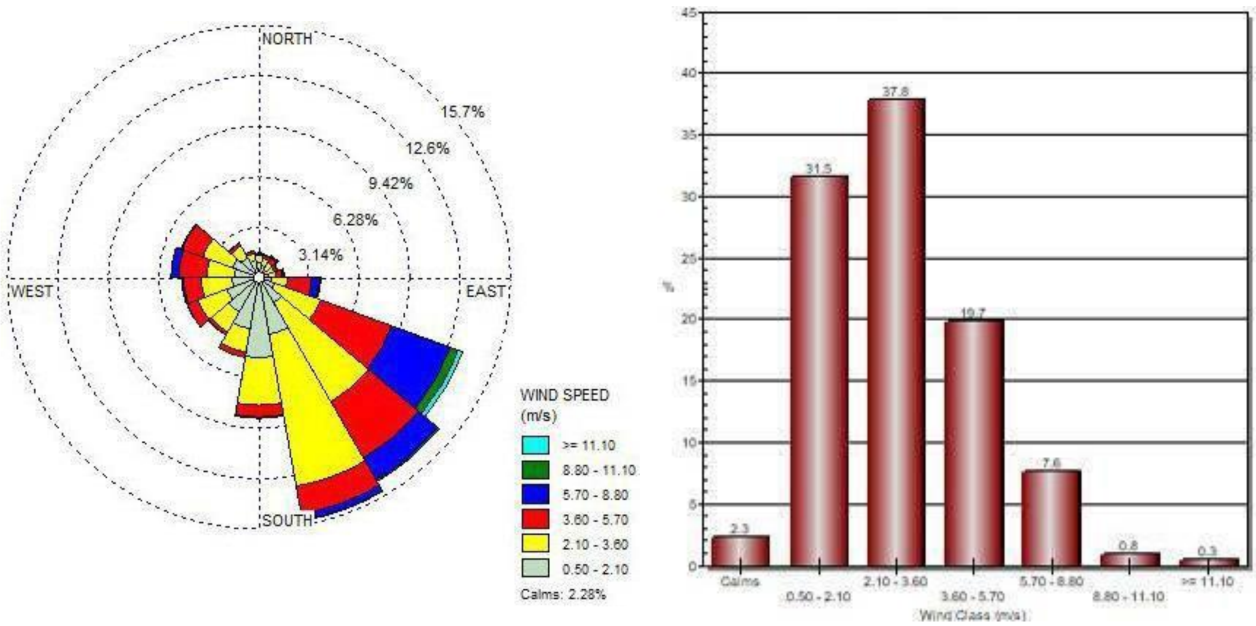


Figure 2.7 Wind rose and frequency chart for 2018.

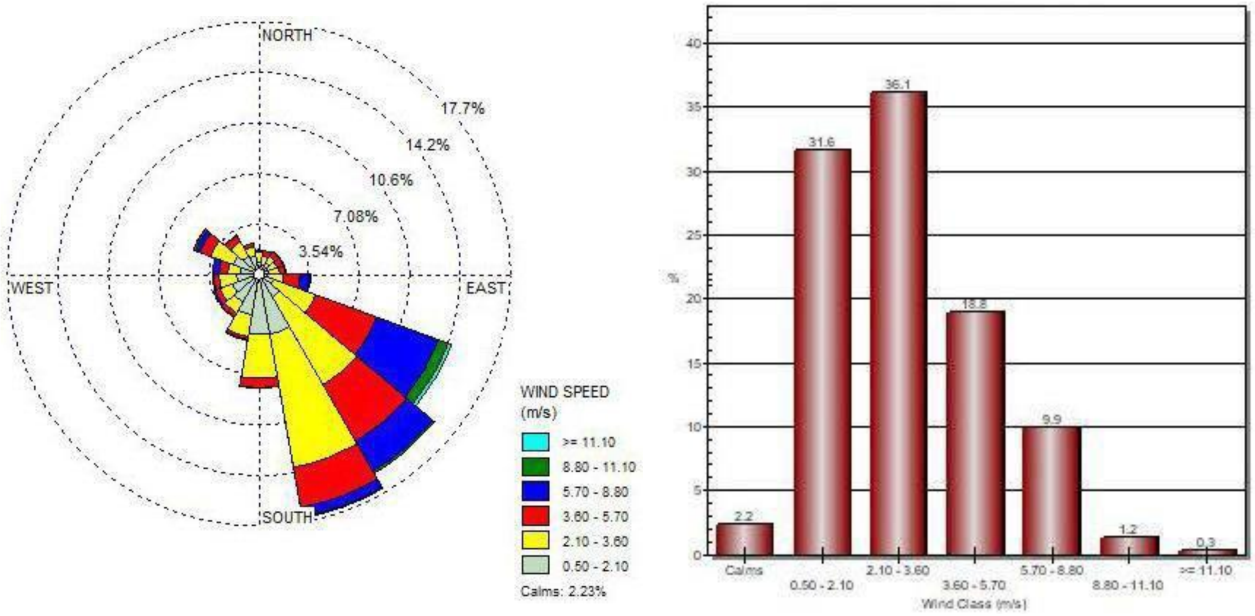


Figure 2.8 Wind rose and frequency chart for 2019.

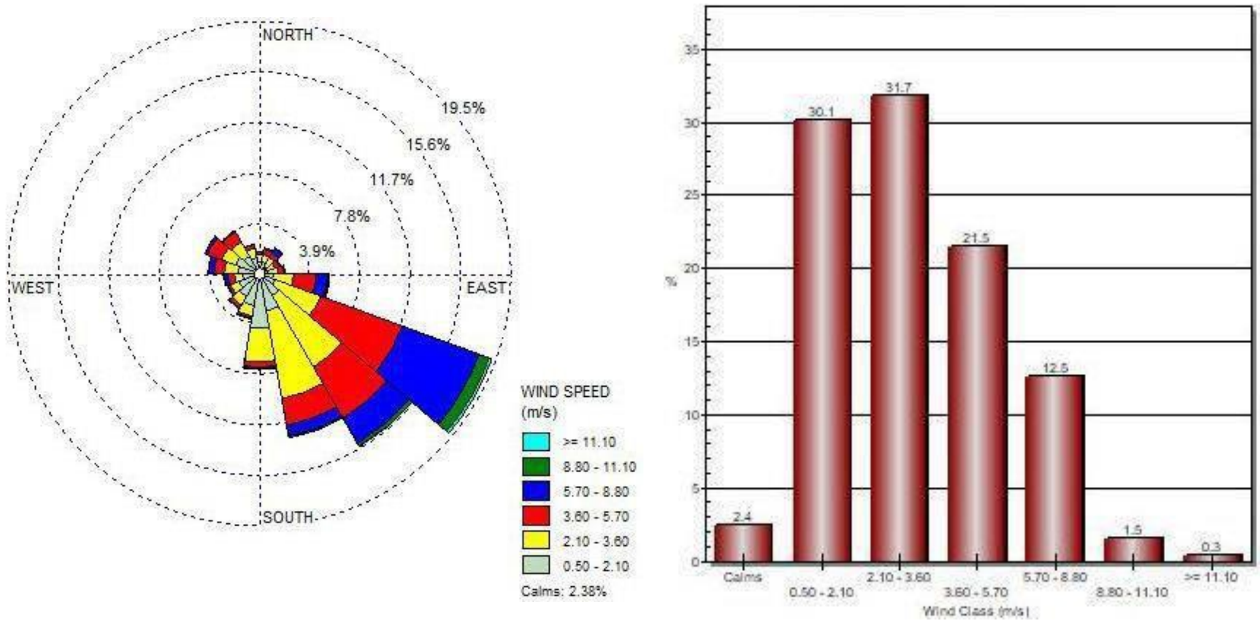


Figure 2.9 Wind rose and frequency chart for 2020.

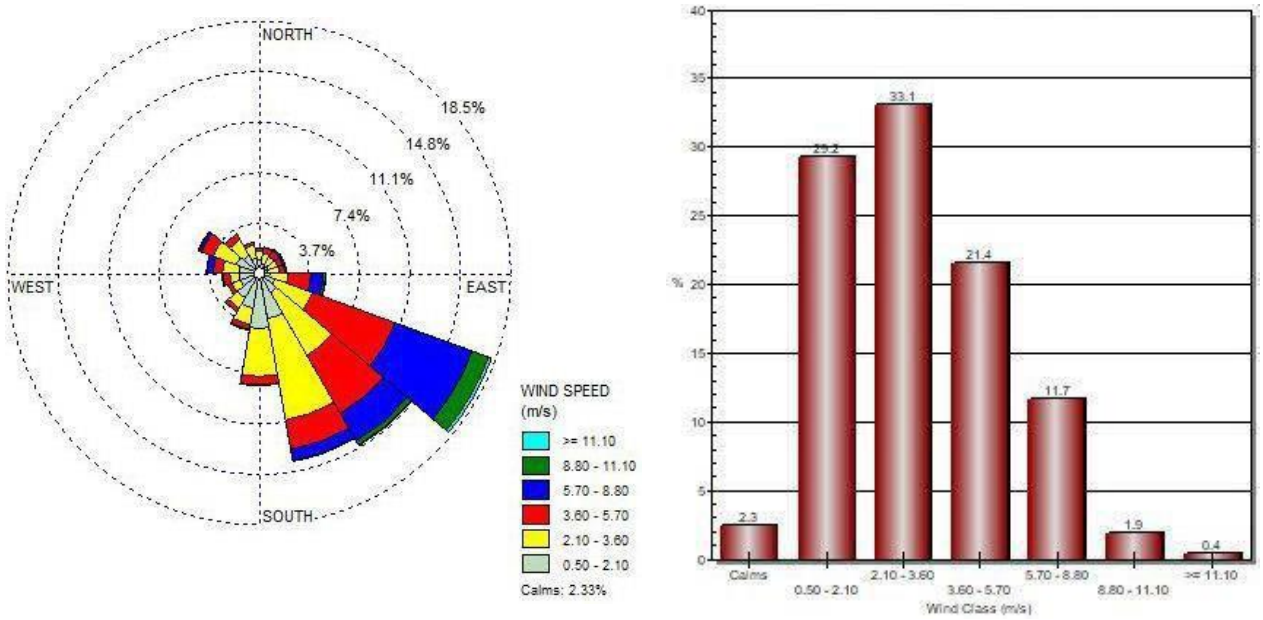


Figure 2.10 Wind rose and frequency chart for 2021.

2.6 Characteristics of source

Appendix I of this Study provides data on emission sources for the case when the waste-to-energy plant operates according to the design parameters used as input parameters for the model.

The operating time of each project activity is also of great importance for an adequate assessment of the impact of the subject plant on air quality. During the creation of the model, in order to model the most unfavorable conditions, the assumption was introduced that during normal operation of the plant, all point sources emit 24 hours, 365 days a year at full capacity, which is certainly not the case. In addition to the plant in question, at the location of the chemical industry complex in Prahovo, no other sources of the pollutants considered by this Study were identified.

When modeling, it is also necessary to take into account the construction facilities on the location, given that their dimensions can greatly affect the dispersion of polluting substances. *Building Downwash* is a phenomenon that occurs when buildings or structures are located in such a way that they represent obstacles in the path of the smoke plume. In this case, the streamlines will rise from the building on the windward side, and descend the leeward side. Immediately behind the building, frictional resistance and a decrease in movement speed appear, which results in the inverse movement of streamlines at ground level, creating recirculation - a region of hollow. As the distance from the building increases, turbulence decreases.

It is necessary to have the following data on objects in the vicinity of the emitter to successfully take into account the possible occurrence of the *downwash effect*:

- geographic coordinates of the observed objects,
- orientation of objects in relation to emitters,
- characteristic dimensions of objects.

For the needs of this Study, also using AERMOD, a 3D model of the chemical industry complex was developed. This model includes only objects significant for dispersion modeling, i.e. objects where a *downwash effect* may occur. Figure 2.11 shows a 3D model of the most significant construction buildings for the future state of the chemical industry complex, with all sources of emissions considered in this Study.

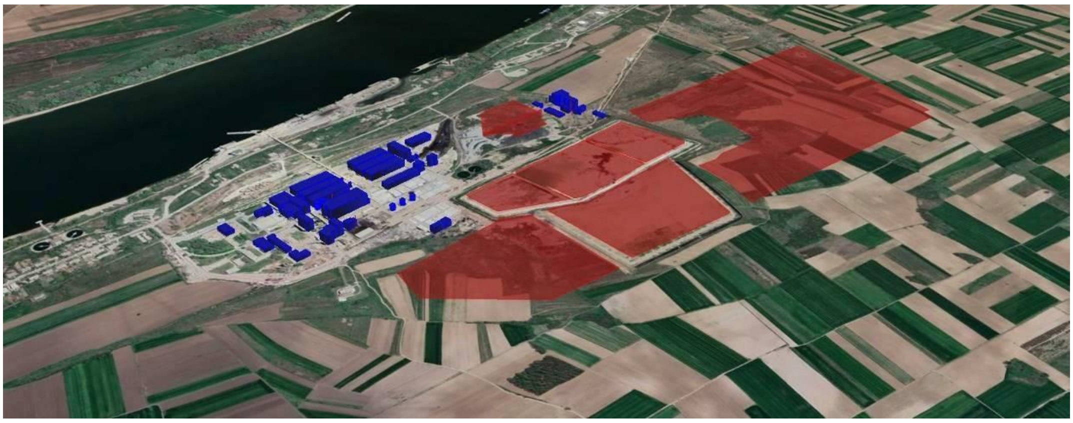


Figure 2.11 3D model of the chemical industry complex in Prahovo, future state

2.7 Requirements for air quality

In order to assess the impact of the operation of a facility on air quality, it is necessary to compare the results obtained by modeling with the corresponding requirements for air quality that are prescribed by national legislation *The Decree on the conditions for monitoring and air quality requirements ("Official Gazette of the Republic of Serbia", No. 11/10, 75/10 and 63/13),* i.e., due to consideration of possible transboundary impact, with EU legislative *Directive (EU) 2024/2881 of the European Parliament and of the Council of 23 October 2024 on ambient air quality and cleaner air for Europe (recast).*

Table 2.1 Air quality requirements[1]

Component and averaging period	*Limit value*
As	
Calendar year	6 ng/m^3
Cd	
Calendar year	5 ng/m^3
Ni	
Calendar year	20 ng/m^3
Pb	
Calendar year	0.5 μg/m^3

Both listed documents (national Decree and EU Directive) prescribe the same limit values.

3. RESULTS

The results of this study, which are given in the form of graphical presentations of ground-level concentrations of pollutants (isopleths), are shown in accordance with the defined method of presentation and averaging periods, as well as the aforementioned legislation.

It should be borne in mind that the results presented in this study represent the highest possible ground concentrations of the considered pollutants, which are the result of the most unfavorable operating parameters and the most unfavorable meteorological conditions during the given averaging period during five consecutive years (from 2017 until 2021). Namely, the potential highest concentration for each of the receptors is shown for the corresponding averaging period over five years.

Due to the way heavy metals are grouped under *BAT* and the fact that air quality limit values are defined only for certain metals, it is necessary to apply a conservative modeling approach to ensure regulatory compliance. Dispersion modeling is performed assuming emissions at the upper limit of the permitted value for each metal group. This means that for Cd + Tl, the maximum allowed *BAT* emission for that group is taken, which is 0.02 mg/Nm^3, i.e. 0.3 mg/Nm^3 for the group Sb, As, Pb, Cr, Co, Cu, Mn, Ni and V. This approach provides the most unfavorable scenario - that is, it is estimated how the dispersion would look in the case when the emissions from the plant are at the BAT limit itself. The obtained concentrations are then compared with the lowest defined limit value for air quality among the regulated metals (As, Cd, Ni, Pb). Since the model considers total concentrations within each metal group (due to the BAT approach), it is not possible to directly decompose the contribution of individual metals. Therefore, the most unfavorable scenario is evaluated by comparing it with the strictest (lowest) regulated value for air quality among those prescribed for As, Cd, Ni, and Pb. If the model shows that the concentrations are below the strictest air quality limit value, it automatically means that they are below the limits for all other metals as well, for the Cd + Tl group it is cadmium with a limit value of 5 ng/m^3, that is As with 6 ng/m^3 for the Sb, As, Pb, Cr, Co, Cu, Mn, Ni, V group. This approach enables a simpler and more conservative assessment, without the need for a complex analytical breakdown of individual components within each metal group.

Figures 3.1 and 3.2 show the isopleths of ground-level concentrations for different groups of heavy metals, with the maximum annual concentrations recorded in the zone of greatest load, along the eastern part of the border of the factories. For the group of cadmium and thallium, the maximum annual concentration is 0.13 ng/m^3, which is several times below the limit value for cadmium of 5 ng/m^3. Similarly, for the group of metals to which arsenic belongs, the maximum annual concentration is 1.9 ng/m^3, while the strictest limit value for arsenic is 6 ng/m^3. These results indicate that future emissions from the considered emitter will not represent a serious problem in terms of long-term air quality, considering that even in the most unfavorable scenarios, the emissions do not reach the prescribed regulatory thresholds.

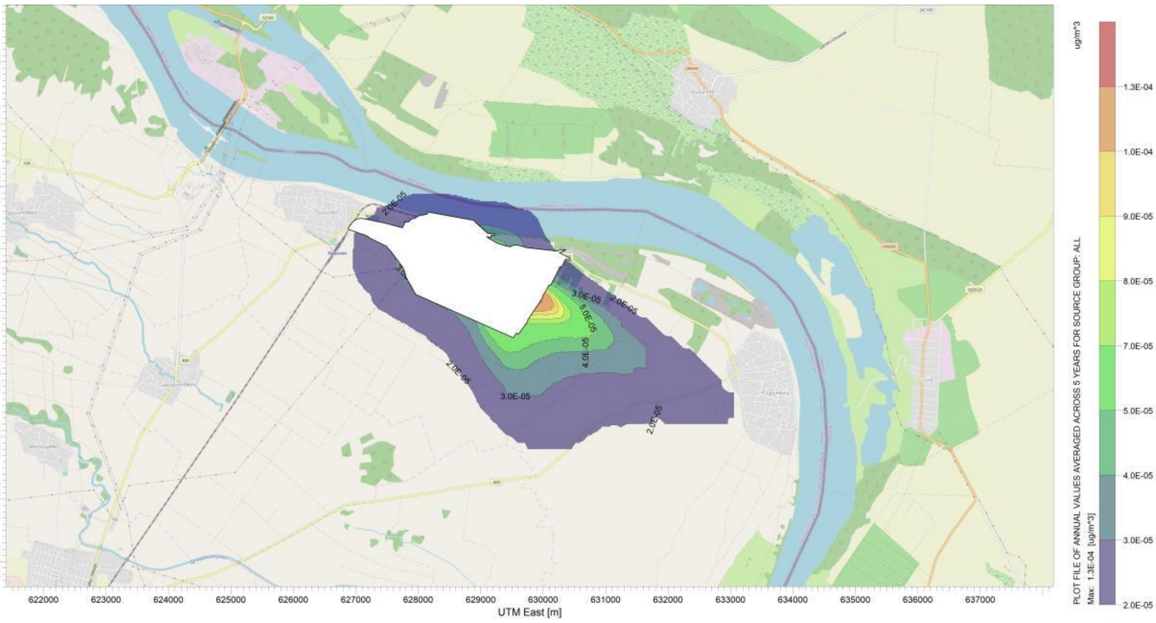


Figure 3.1 Maximum ground-level concentrations (Cd+Tl) - annual average [μg/m^3]

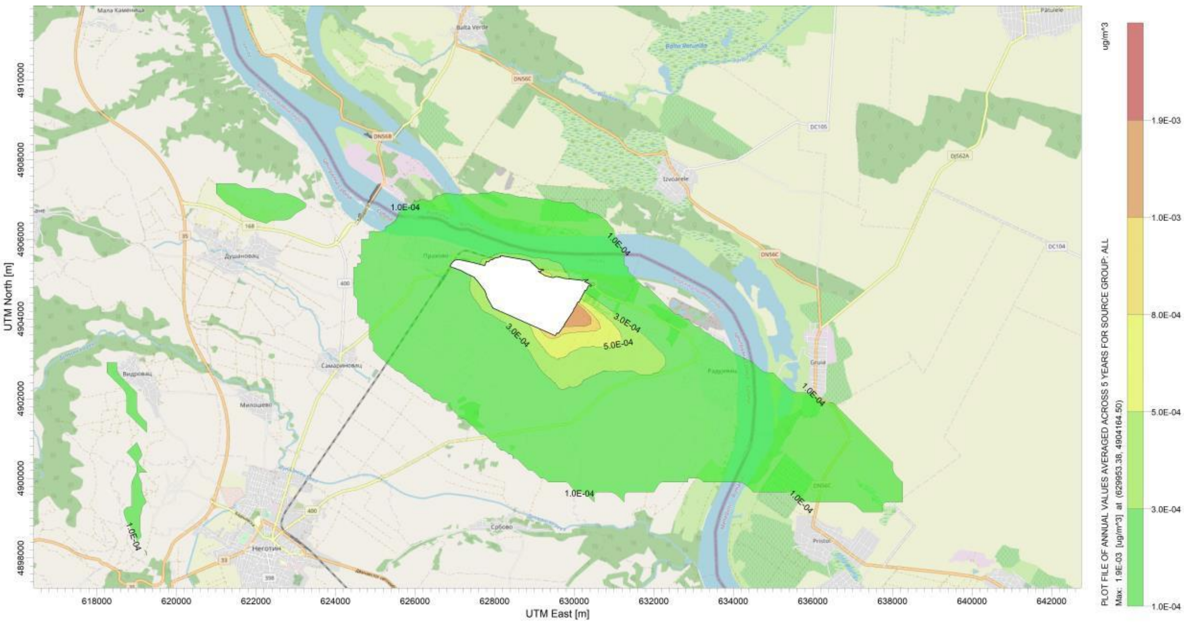


Figure 3.2 Maximum ground-level concentrations (Sb, As, Pb, Cr, Co, Cu, Mn, Ni, V) – annual average[μg/m^3]

4. CONCLUSION

Based on the modeling results, it can be concluded that heavy metal emissions from the Waste-to-energy plant do not pose a risk to air quality in the wider area of the chemical industry complex in Prahovo. Modeling was used to analyze the contribution of heavy metal emissions from the point emitter of the boiler plant of the Waste-to-energy plant, where the results showed that at no time did the concentrations exceed the prescribed target values for air quality defined by European and national regulations.

The modeling approach was conservative, which means that the emissions were simulated at the maximum allowed values according to the emission limit values from the corresponding *BAT* conclusions. Two groups of metals were analyzed - the first, which includes cadmium and thallium, and the second, which includes arsenic, lead, nickel, chromium, cobalt, copper, manganese, nickel, and vanadium. By comparing the obtained concentrations with the lowest prescribed target values for air quality, it was determined that even in the most unfavorable scenario, emissions do not threaten air quality standards.

The maximum annual average concentration for cadmium and thallium was 0.13 ng/m^3, which is significantly below the target value of 5 ng/m^3. For the group of metals to which arsenic belongs (the metal with the lowest limit value from that group), the maximum modeled concentration is 1.9 ng/m^3, while the limit value is 6 ng/m^3, which means that the emissions remain within the permitted limits. The spatial distribution shows that the pollution spreads dominantly in the southeast direction, following the dominant wind directions.

Modeling results show that regulatory limits are not exceeded even in the immediate vicinity of the emission source, while concentrations in remote areas are many times lower. In conclusion, the modeling results confirm that the emissions from the planned plant will not negatively affect the air quality in the analyzed area, including the potential cross-border impact on Romania and Bulgaria.

APPENDIX I

DATA ON EMITTER

Emitter name: E18 – Boiler plant emitter (W-C14)		
Parameter	**Value**	**Unit**
Emitter height	56 m in relation to level 0	[m]
The inner diameter of the emitter at its top	1.7	[m]
Flue gas temperature at the top of the emitter	147 ± 3	[°C]
Flue gas volume flow through the emitter	70,000	[Nm^3/h]
Mass flow of Cd+Tl	0.0014	kg/h
Mass flow of Sb+As+Pb+Cr+Co+Cu+Mn+Ni+V	0.021	kg/h
Geographical coordinates of the emitter	44.284570 22.616845	[Lat/Long]