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The impact of heating systems scenarios on air pollution at selected residential zone: a case study using AERMOD dispersion model

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Abstract

The present case study considers fuel base substitution in operation of actual district heating system and in other scenario replacing of district heating system by individual heating system in each apartment building and non-residential building in selected residential zone Zvolen-Sekier, Slovakia. The impact of each heating system was assessed with focus on ambient air quality based on air dispersion modelling of NO_2 and CO pollutans using the AERMOD dispersion model. To identify the exposure level on residents, the magnitude and duration of exposure to the hazard were considered according to human health risk assessment method. Results showed that the individual heating systems released significantly higher NO_2 and CO concentrations directly in the residential zone compared to district heating system. The obtained results were highly variable for individual scenarios and averaged periods of pollutants concentration. Investigated heating systems scenarios showed low (< 1.0) hazard quotient value, however, individual heating systems would lead to adverse health effects, especially in infants and children population.

Keywords AERMOD, Air pollution, Dispersion modelling, Energy demand, Health risk assessment, Heating system

Introduction

The growth of population and gross domestic product is associated with an increase in energy demand. Ensuring energy can be realized in the form of heating, cooling, and electricity. Two basic systems, district heating system (DHS) and individual heating system (IHS), can be used to provide heating for residents [25]. The DHS is typical in most post-socialist countries of Central and Eastern Europe, including the Slovak Republic, as the main source of universally accessible energy service and plays a major role in heating markets of these countries [38, 55]. District heating is often considered as an environmentally friendly form of heat supply [55]. According to Guzzini et al. [14], DHS is considered as the best option since it´s ability to ensure a better control of pollutant emissions and greater efficiency than IHS.

The advantages of district heating such as high fuel efficiency, lower heat production capacity requirement and cheaper fuels most often make DHS cost efficient, especially in densely populated areas where the heat loss are low [18].

Due to the fact that Slovak republic is a country that has a large gasification, favourable natural gas prices for protected customers and available boilers with high efficiency, especially in recent years, there has been a significant trend of disconnection of apartment buildings and various non-residential buildings from DHS and construction of IHS was carried out. Disconnecting from DHS is primarily motivated by the expectations of residents for reduction in heat supply costs. Therefore, DHS is compared with IHS by the cost point of view most often

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[39]. However, it is not only the economic aspects that need to be taken into account, but also the environmental aspects of the disconnection of the population from DHS and the operation of IHS. Heat production is associated with the production of various pollutants, such as PM_{10}, $PM_{2.5}$, NO_X, SO_2, CO and CO_2 [23]. A larger number of small heat sources to ensure energy demands also represents a larger number of stationary point sources emitting pollutants in the atmosphere [27].

So called small sources of emissions (with total rated thermal input < 0.3 MW) not necessarily equate to a smaller volume of emissions. In fact, emissions from smaller sources are several times higher than those from larger sources. The control of air pollutant emissions from such sources is practically non-existent due to inadequate legislative requirements and insufficient resources allocated to cities and municipalities [2]. Air quality in terms of the impact on the health of the population can thus become unsatisfactory not only in industrial but also in residential zones [27].

According to Baykara et al. [4], emissions from IHS play an important role in urban air pollution, especially during winter seasons. Compared to point sources with higher release rates of pollutants, IHS release rates are significantly lower, leading to potentially higher human exposure. Combined with the low vertical agitation during winter, emissions from the IHS heating sector are becoming one of the main contributors to local air pollution.

According to Braniš et al. [5], despite the spreading natural gas distribution network in last decades, heating in most small towns and villages in Central and East European countries is still based on combustion of wood and low quality coal. Also kerosene, biomass (wood, animal dung and crop waste), and waste such as plastics and tyres are commonly used in poor regions. World Health Organization [56] stated that over 4.2 million people a year die prematurely from illness associated with household air pollution caused by the inefficient use of solid fuels and kerosene for cooking and heating. This effect is likely to exacerbate in the near future due to the European Union´s plans to reduce Russian gas imports which will resulted to the expected shortage and high natural gas prices. This issue is very widespread and beyond the scope of this article.

Air dispersion models play a pivotal role in understanding and mitigating local air pollution. Several widely used models, including AERMOD, ISC3, ADMS, and CALPUFF, are employed for this purpose. Each model has unique features and advantages, making them suitable for different applications. AERMOD (American Meteorology Society-Environmental Protection Agency Regulatory Model), developed by the U.S. EPA, is renowned for its versatility and accuracy. It considers complex terrain, various meteorological conditions, and different sources of emissions. AERMOD's advanced algorithms and regulatory acceptance make it a preferred choice for many environmental impact assessments. ISC3 (Industrial Source Complex Mode), also developed by the U.S. EPA, is a screening model suitable for simple terrain and near-field applications. It provides quick estimates of pollutant concentrations and is often used for regulatory compliance checks. However, its simplicity may limit its accuracy in complex environments. ADMS (Atmospheric Dispersion Modelling System) is widely used in Europe and is known for its user-friendly interface. It considers a range of sources, emission types, and complex terrain. ADMS is suitable for local-scale studies, making it valuable for urban air quality assessments. The performances of AERMOD and ADMS models have been tested in several studies involving stack emissions under various meteorological and topographical conditions [7, 41], Harsham and Bennet, 2008). Furthermore, the results from AERMOD and ADMS have been tested against measured results of gaseous emissions in flat and complex terrain, respectively [17, 40]. According to above mentioned studies, the dissimilarities between AERMOD and ADMS models, especially in their meteorological preprocessors and dispersion algorithms, lead to divergent pollutant concentration predictions in certain scenarios. Due of these variances, it is impossible to conclusively ascertain which of these models is better suited for a specific application.

According to Hanna et al. [16], by comparing AERMOD, ADMS and ISC3 (Industrial Source Complex), the ISC3 model typically overpredicts pollutans concentrations. The ADMS performance is slightly better than the AERMOD performance and both perform better than ISC3. On average, ADMS underpredicts by about 20% and AERMOD underpredicts by about 40%, and both have a scatter of about a factor of two.

CALPUFF is a Lagrangian puff dispersion model capable of simulating long-range and short-range transport of pollutants. It handles complex terrain and meteorological conditions, making it suitable for regional and urban-scale modeling. CALPUFF is often chosen for studies involving pollutants with long-range transport potential. According to Tartakovsky et al. [47], AERMOD predictions were in a better agreement with the measurements than those obtained by CALPUFF. On the other hand, according to Gulia et al. [15], satisfactory performance of CALPUFF over AERMOD might be due to its preditcing capability in calm condition, in which all plume dispersion models failed. According to Mateusz [26], CALPUFF model may be used for regulatory purposes on a local scale only in justified cases, since AERMOD is currently more preferable model by the U.S. EPA. AERMOD is recommended model when estimating the air quality impact of emissions from the receptor of concern is approximately less than 50 km from the source [35]. The CALPUFF model, unlike AERMOD, has the capabilities of handling both mesoscale and long range dispersion calculations; hence it is recommended for dispersion calculations from about 50–1000 km [48] and [1].

The HYSPLIT (Hybrid Single Particle Lagrangian Integrated Trajectory) model is a hybrid non-steady-state puff/particle plume dispersion model, meaning it simultaneously combines both puff and particle approaches to modeling an emission plume. The original purpose of this model was to function as a swiftly deployable online regional model for dispersing pollutants. It aimed to offer short-term air quality simulations, ranging from 1 h to a few days, primarily for emergency services. The model's key feature is its ability to calculate trajectories, enabling the identification of local or remote sources of observed air contaminants. The HYSPLIT model is most effective within a geographic domain spanning approximately 10–50 km [10].

By comparing with other models, AERMOD's accuracy, flexibility in handling diverse sources and terrain, and regulatory acceptance make it an ideal choice for modeling local air pollution. Its robust capabilities empower researchers to conduct detailed and reliable assessments, ultimately aiding in effective pollution management and policy formulation. For correlating long-term exposures at deployed locations to future health outcomes, AERMOD would be the model of choice due to its very long timescale and simple output.

The aim of this paper is to evaluate the impact of hypothetical massive disconnection of households and commercial sector from DHS in the selected residential zone Zvolen-Sekier on ambient air quality based on modelling of dispersion of pollutants using the U.S. EPA preferred AERMOD dispersion model. The case study considers replacing DHS with small sources of air pollution in each apartment building and non-residential building in this residential zone. Also, an alternative fuel substitution of biomass and lignite by natural gas at DHS plant was considered.

Material and methods

Description of the study area

The present study focuses on the residential zone Zvolen-Sekier situated in the city territory of Zvolen in central Slovakia. The total area of the Zvolen city is 98.73 km^2. With approximately 43,000 inhabitants, and it is the twelfth most populated municipality in the Slovak republic. Currently, the density of the population is 426.33/km^2 [45].

The study area is located in the southern region of the Zvolenská Kotlina basin. The river Hron and the river Slatina formed river terraces and the city of Zvolen has developed since mediaeval ages on one of the terraces. The Zvolenská Kotlina basin is one of the basins of the Western Carpathians that have strongly rugged terrain. The altitude ranges from 290 m above sea level (masl) to 851 masl. The climate in the studied area is continental, with a maximum of 27 °C in July (summer). In winter, maximum temperatures are around 0 °C, with an average minimum of –3 °C. Average annual precipitation is 685 mm [42].

The model domain consists of a square area centred in residential zone Zvolen-Sekier (at $X = 364{,}042.40$; and $Y = 5{,}380{,}590.58$) with the domain boundaries summarized in Table 1.

Determined study domain includes an area which extends beyond the residential zone itself, but it is an area in its immediate vicinity which has been chosen to better understand the distribution of pollutants. It is necessary to mention that the closest distance between existing DHS plant and residential zone Zvolen-Sekier is only approximately 700 m. Therefore, there is a reasonable concern about the assessment of the impact of this source of emissions on the health of the population.

The model domain was discretized at 441 receptors using a uniform Cartesian grid in AERMOD. Receptors' heights were considered at ground level.

Dispersion modelling

The air dispersion modelling approach was based on the American Meteorological Society (AMS) and U.S. Environmental Protection Agency (U.S. EPA) Regulatory Model (AERMOD). Due to its extensive development, the AERMOD is currently the most recommended dispersion model in the U.S. EPA. Specifically, AERMOD View software (v.10.0.1, Lakes Environmental, Waterloo, ON, Canada) was used to perform air dispersion calculations.

The AERMOD is considered a state-of-art modelling system based on planetary boundary layer (PBL) turbulence structure and scaling concepts, including treatment

Table 1 Domain boundaries and parameters

Domain axis	Length [m]	Spacing [m]	Boundary points UTM 34N [m]
X Axis	4003.60	200.18	360,546.28 (X_{min}) 369,346.91 (X_{max})
Y Axis	4014.00	200.70	5,377,813.53 (Y_{min}) 5,383,284.05 (Y_{max})

of both surface and elevated sources, and both simple and complex terrain. The model set up requires three main steps: meteorological and land cover data processing by AERMOD meteorological pre-processor (AERMET); elevation data processing by AERMOD terrain pre-processor (AERMAP); and AERMOD Gaussian plume model that performs the dispersion calculations [37]. AERMET uses PBL, which serves as a replacement to the Pasquill–Gifford stability classes previously used by plume dispersion models. AERMOD calculates the effects of vertical variation of wind, turbulence profiles and temperature [12].

The 1-h, 8-h (only for CO pollutant) 24-h, and average concentration values were calculated for a study domain in complex terrain. For simplicity, we considered the complete conversion of NO_X to NO_2 as the worst case situation.

Meteorological and terrain data

Weather conditions, especially wind speed, wind direction and ambient temperature affect air dispersion of pollutants in Zvolenská Kotlina basin. Moreover, as can be seen in Fig. 1, study area is significantly affected by local orography which causes low wind velocity and frequent calm winds and inversion situations in winter season [43]. Topographic map of study area in Fig. 1 was prepared by a digital elevation dataset obtained during the Shuttle Radar Topography Mission (SRTM3) with resolution of 90 m [9]. Digital elevation data were preprocessed by AERMAP (U.S. [49].

Hourly meteorological data from 2013 to 2021, as an input for AERMOD were used. Meteorological data were obtained from the Automated Surface Observing System (ASOS) situated at Sliač airport (5,388,981.31N, 362,816.25E; 313 masl) which is located approximately

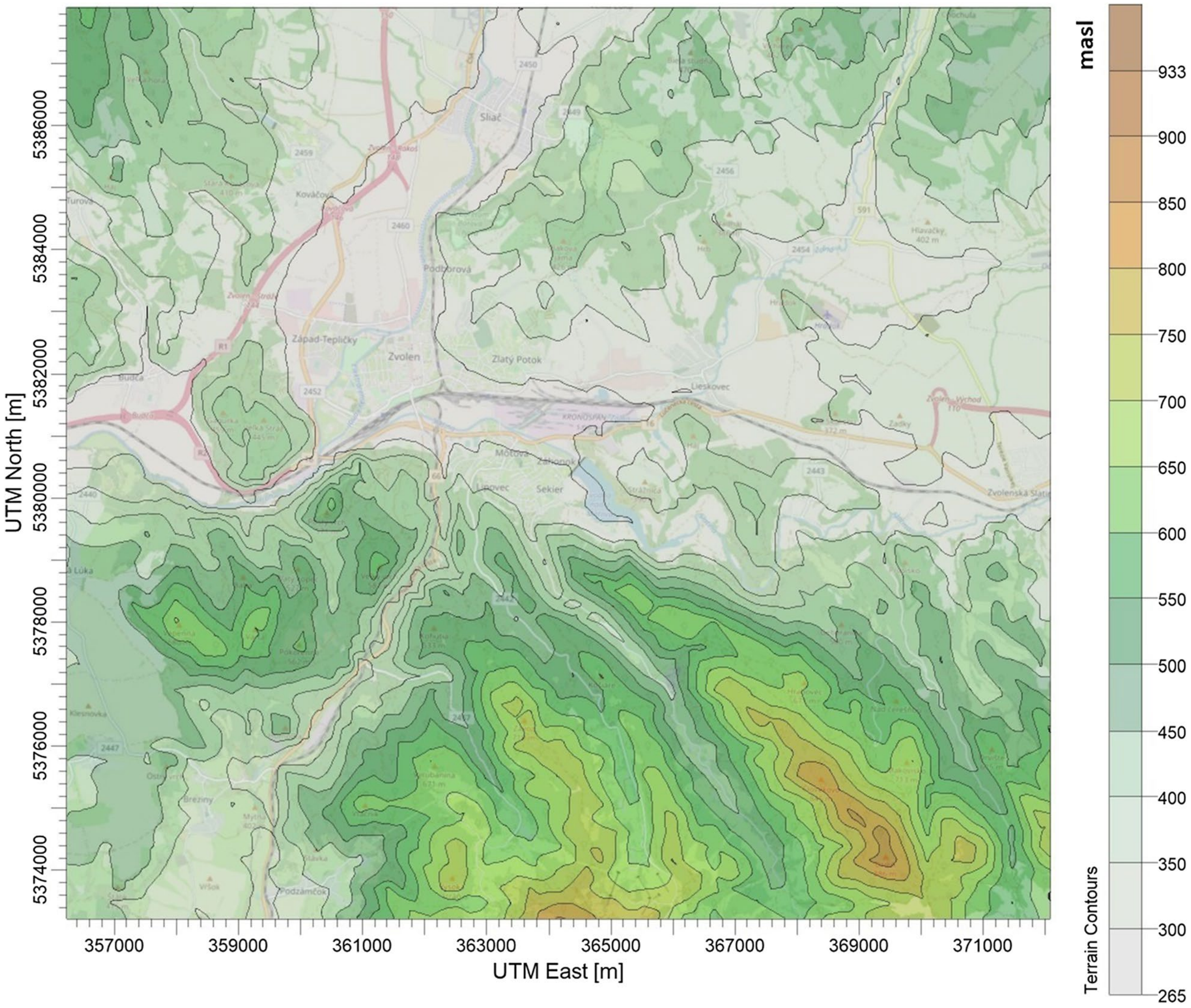

Fig. 1 Elevation contours based on SRTM digital elevation dataset in Zvolen and surroundings

9 km northern from investigated residential zone Zvolen-Sekier. According to U.S. EPA´s memorandum, the ASOS meteorological data are suitable for application in AERMOD model (Fox, 2013). The raw meteorological data were arranged into the SAMSON format (.SAM). Upper air data were purchased from the AERMOD service hub as AERMET-Ready Weather Research and Forecasting (WRF) met data. Subsequently, surface meteorological data were processed into the FSL format (.FSL) by meteorological data preprocessor AERMET (AERMET View v.10.0.1, Lakes Environmental, Waterloo, ON, Canada). The output from AERMET were surface data file (.SFC) and profile data file (.PFL) required by AERMOD model. Output data were checked by a quality assessment process for missing data, or data outside the range of acceptable values. For this purpose, default surface variable ranges in AERMET were used (U.S. [50]. Surface roughness, albedo and Bowen ratio were selected for urban land use type and annual average season conditions.

Complete available meteorological data were carefully chosen for main heating season months that we considered from 1 September to 31 December and from 1 January to 30 April of each year. According to wind rose (Fig. 2), prevailing wind direction in study area is the northern wind. The average wind speed during heating season is 1.96 m/s and average percentage of calm situations is approximately 20%. This meteorological conditions relates to the Zvolenská Kotlina basin inverse position.

Evaluated heating systems scenarios

Existing district heating system (scenario 1)

Production and heat supply is the primary activity of investigated DHS located in Zvolen-Sekier area. Power plant with parameters shown in Table 2 focus mainly on central heating and domestic hot water (DHW) preparation for communal sector, and industrial activities as well. Part of the produced superheated steam (540 ± 5 °C) is used to produce electricity in a back-pressure turbine with 25 MW$_e$ generator and voltage of 6.3 kV.

DHS as the source of air pollution consists of two boiler units, which are venting into a common stack with

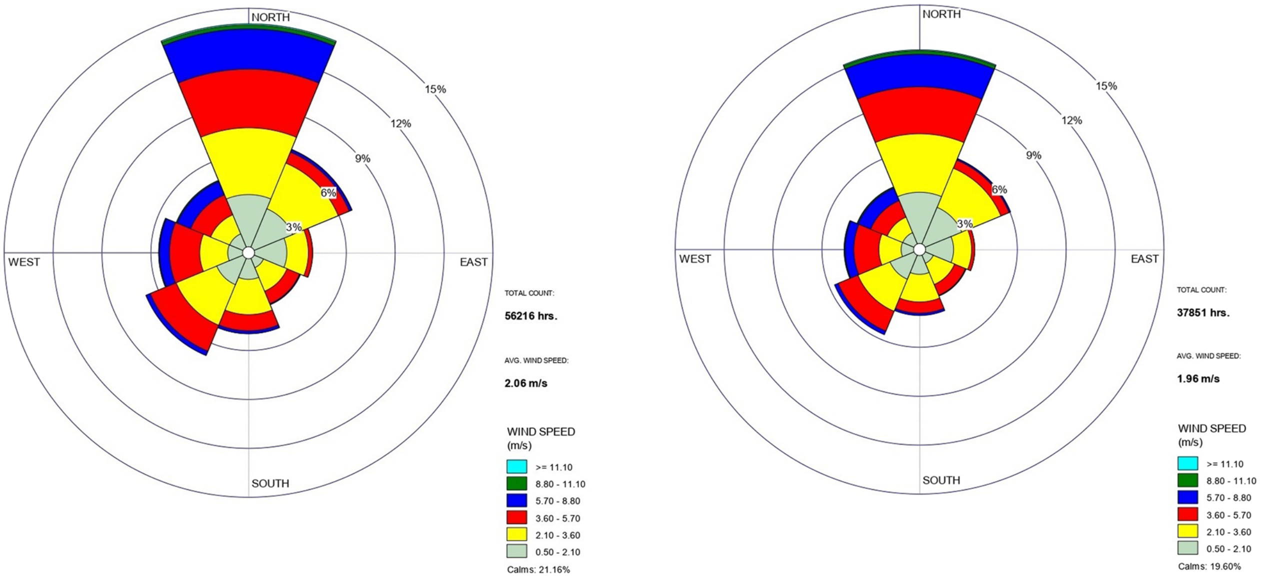

Fig. 2 Windrose diagram for data period from 1 January 2013 to 31 December 2021 (left) and windrose diagram for heating season months (right). Compiled using WRPlot View (v.10.0.1, Lakes Environmental, Waterloo, ON, Canada).

Tab 2 Technical parameters of existing DHS

Boiler units	Total rated thermal input	Steam output	Efficiency	Fuel type	Commissioning
–	[MW]	[t/h]	[%]	–	–
Boiler B1	39.50[1]	55.00	83.00	woodchips, lignite	1990
Boiler B2	39.50[2]	55.00	83.00	woodchips, lignite	1991

[1] Thermal input of boiler was reduced from 126 MW after power plant modernisation in 2020

[2] Thermal input of boiler was reduced from 75 MW after power plant modernisation in 2020

a height of 183.00 m. Primary deNO$_X$ methods and electrostatic precipitators are used to reduce pollutants in flue gas. Boiler B2 serves as a cold backup for boiler B1. Both boiler units are constructed as single-drum steam granulation boilers with membrane walls and natural circulation. The boilers are designed for primary combustion of lignite (low-sulphur content with a calorific value from 13.00 to 20.00 MJ/kg is used), including co-combustion of woodchips (calorific value from 8.50 to 12.00 MJ/kg), and natural gas as fuel stabilizer.

Table 3 shows input data for AERMOD dispersion model in Scenario 1. Data were obtained from the Continuous Emission Monitoring System (CEMS) which is a mandatory part of the operation to monitor the flue gas streams resulting from combustion in such industrial process. Data from CEMS represent period from 2013 to 2021 during main heating season months (September–April).

Technology and fuel base substitution at district heating system (scenario 2)

Scenario 2 represents the potential reconstruction of DHS and complete fuel base substitution for power plant. The using of biomass and lignite in existing boiler B1 was replaced by 100% natural gas combustion in two hot water boilers (HWB) with parameters shown in Table 4. Up-to-date HWB with an economiser are considered as an appropriate solution in increasing the efficiency of existing power plants which is one of the priorities in line with the EU's commitments to reduce greenhouse gas emissions and achieve several other environmental goals [13].

In Scenario 2, the flue gas with parameters shown in Table 5 was considered. Flue gas emissions in the ambient air were modelled through separate stack from each HWB.

Individual heating systems (scenario 3)

Design of IHS depends on the specific situation, especially on the energy parameters of the building, the economic aspect, the location in which the building is situated and many other factors which cannot be generalized. For the purpose of this study, we considered gas-fired condensing boilers as substitution of DHS in all local apartment buildings, retirement home, school buildings and other commercial objects (non-residential buildings) in residential zone Zvolen-Sekier.

Gas-fired condensing boilers are suitable for individual houses, as well as, for entire apartment buildings and non-residential buildings. Usually, individual house with

Table 3 Input data for AERMOD dispersion model in scenario 1

Parameter	Unit	Value
Stack (release) height	[m]	183.00
Stack hydraulic diameter	[m]	4.85
Level of O$_2$ in flue gas[1]	[vol-%]	13.13
Flue gas temperature[1]	[°C]	160.39
Flue gas volume flow (standard conditions) 1)	[Nm^3/s]	36.18
Flue gas volume flow (operational conditions) 2)	[m^3/s]	59.85
Flue gas velocity	[m/s]	1.96
NO$_X$ emission rate[3]	[g/s]	28.57
CO emission rate[3]	[g/s]	3.03
SO$_2$ emission rate 3)	[g/s]	40.87
PM emission rate[3]	[g/s]	2.18

[1] Data reported by CEMS. Standard conditions refer to 0 °C (273.15 K) and 101,325 Pa

[2] Real operational conditions were recalculated by the Combined Gas Law Formula

[3] Emission rate of pollutants expressed at real operational conditions

Table 5 Input data for AERMOD dispersion model in scenario 2

Parameter	Unit	Value
Stack (release) height	[m]	2×31.90
Stack hydraulic diameter	[m]	2×0.80
Level of O$_2$ in flue gas	[vol-%]	2.10–3.00
Flue gas temperature	[°C]	97.00
Flue gas volume flow (standard conditions)	[Nm^3/s]	3.30
Flue gas volume flow (operational conditions)	[m^3/s]	4.47
Flue gas velocity	[m/s]	8.90
NO$_X$ emission rate[1]	[g/s]	0.40
CO emission rate[2]	[g/s]	0.07

[1] Emission rate of NO$_X$ was calculated at the level of guaranteed emission 90 mg/Nm^3 and expressed at real operational conditions

[2] Emission rate of CO was calculated at the level of guaranteed emission 15 mg/Nm^3 and expressed at real operational conditions

Table 4 Technical parameters of HWB as alternative technology and fuel base in scenario 2

Boiler units	Total rated thermal input	Steam output	Efficiency	Fuel type	Fuel consumption
–	[MW]	[t/h]	[%]	–	[m^3/h]
HWB1	10.34	18.95	96.00	natural gas	1034.00
HWB2	10.34	18.95	96.00	natural gas	1034.00

floor area about 100 m^2 requires only one boiler unit. On the other hand, for apartment buildings and non-residential buildings two or more boiler units connected in cascade are appropriate. In this way, the installed capacity of gas condensing boilers can be effectively increased, and individual boilers can also be switched on and off according to current requirements. Thus, one of the most significant advantages of cascade connection is the variability of boiler room.

Table 6 shows the basic parameters of the most common gas-fired condensing boilers used in residential and non-residential buildings on the basis of information obtained from the manufacturers of these devices and companies dealing with their installation in Slovakia, respectively.

According to Slovak Innovation and Energy Agency [44], typical heat demands in Slovakia for average apartment with 70 m^2 floor area require approximately 4.50 kW for heating and 2.00 kW for DHW preparation, respectively. In total, 6.50 kW of heat supply is needed for average apartment with 70 m^2 of heated floor area.) The number of apartments in buildings varies, because several architectural types of apartment buildings were built in Slovakia, especially during the 1960s and 1980s. Apartment buildings type A (Fig. 3) and type B (Fig. 4) occurred in investigated residential zone. Moreover, it is a common phenomenon to connect buildings Type A into larger blocks with three entrances [29].

The following parameters of the average apartment building in investigated residential zone shown in Table 7 were considered.

To obtain the required thermal power of the apartment building the parameters of boiler units shown in Table 6. Cascade connection and adequate thermal power and

Table 6 Parameters of gas-fired condensing boilers considered as reference devices

Type of gas-fired condensing boiler	Thermal power [kW]	Fuel consumption [m^3/h]	Stack diameter [mm]	Flue gas temperature [°C]
BUDERUS Logamax plus GB162	100	10.50	200–250	76
BUDERUS Logano plus GB312	240	24.40	200–250	75
VIESSMANN Vitodens 200-W	150	15.00	200–250	74
VAILLANT ecoTEC plus VU 80–120 kW	120	12.10	200–300	85
WOLF MGK2	130	13.10	250–300	65
	170	16.80		65
	210	21.00		65

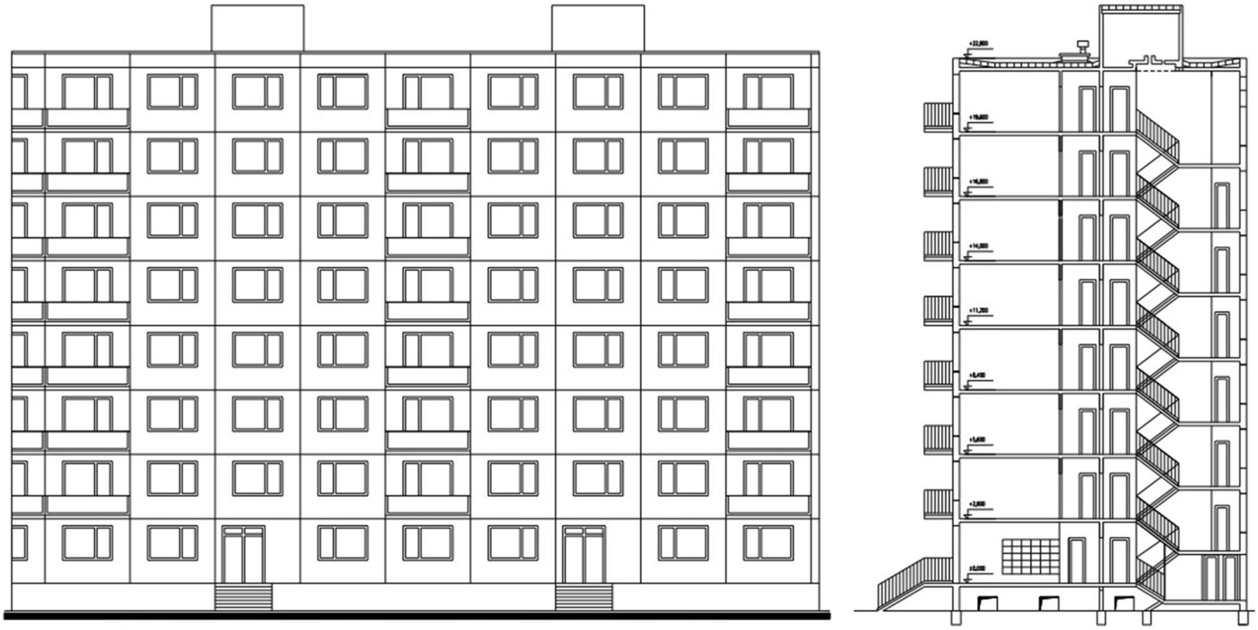

Fig. 3 Architectural section drawings of apartment building type A: front view (left) and cross-section in side view (right)

Fig. 4 Architectural section drawings of apartment building type B: front view (left), side view (centre) and cross-section in side view (right)

Table 7 Types of apartment buildings in study area and heat demand specification

Parameter	Unit	Type A		Type B
Building height	**[m]**	**22.80**	**22.80**	**25.67**
Number of entrances	–	2	3	1
Number of floors	–	8	8	8
Number of apartments at each floor	–	3	3	3
Total number of apartments in building	–	48	72	24
Heating demand for a building during heating season	[kW]	312	468	156

Table 8 Emission factors for natural gas combustion

Boiler Unit Type	Thermal Power	PM	SO_2	NO_X	CO
–	[MW]	[kg/10^6 m^3 of natural gas]			
Gas-fired Condensing Boilers With Low-emission Burner	≥ 0.30 ÷ < 1.00	0.00	0.00	538.40	146.10

Note: emission factors refer to natural gas combustion from the public distribution network in Slovakia

corresponding natural gas consumption were calculated. Natural gas consumption was the key factor for the subsequent calculation of pollutants emission rate based on emission factors for natural gas combustion shown in Table 8. An average fuel consumption for 156 kW, 312 kW and 468 kW boiler room was 15.76 m^3/h, 31.20 m^3/h and 47.27 m^3/h, respectively.

Based on the emission and fuel consumptions Inventory for medium and large stationary sources in Slovak republic, the average thermal power of boiler room in school buildings ($n = 249$) is approximately 564 kW, which corresponds to 56.97 m^3/h of natural gas (SPIRIT, 2023). To meet the aim of the study, the same thermal power and fuel consumption was considered for other non-residential buildings.

Emission factors in Table 8 were compiled on the basis of current measurements of gas-fired condensing boilers for regulatory purposes. The flue gas parameters considered in Scenario 3 are shown in Table 9.

More detailed AERMOD´s input data on each individual heating system considered in this study are available in Additional file 1.

Human health risk assessment

The aim of Human Health Risk Assessment (HHRA) is to identify the population exposed to the hazard, the magnitude and duration of exposure to the hazard. Our study assumed the inhalation route as the major route of exposure to the investigated NO_2 and CO pollutants.

Table 9 Input data for AERMOD dispersion model in scenario 3

Parameter	Unit	Type A		Type B	Non-residential buildings
Number of entrances	–	2	3	1	–
Stack (release) height[1]	[m]	24.30	24.30	27.17	[2]
Stack hydraulic diameter	[m]	0.25	0.30	0.20	0.30
Flue gas temperature	[°C]	72	72	72	72
Flue gas volume flow (wet)	[m^3/h]	380.32	576.20	192.11	694.44
Flue gas volume flow (dry)	[m^3/h]	318.95	483.22	161.11	582.38
Flue gas velocity	[m/s]	1.80	1.90	1.42	2.29
NO_X emission rate	[g/s]	4.67E-03	7.07E-03	2.36E-03	8.52E-03
CO emission rate	[g/s]	1.27E-03	1.92E-03	6.40E-04	2.31E-03

[1] Release height for apartment buildings was calculated in the accordance with Slovak Republic Act on Clean Air 137/2010 as amended as building height shown in Table 7 plus 1.50 m

[2] Release height for non-residential buildings was set individually for each building in range from 6.50 to 20.50 m

The HHRA is a predictive estimating of the exposure risk to a known pollutant. The HHRA framework uses existing exposure data to measure the health effects of human exposure to chemical of interest [30, 34]. Human exposure was explained in terms of the average daily dose (ADD) and was computed according to EPA´s current methodology (U.S. [52], described by the following Eq. (1):

$$ADD = \frac{C_{air}\, x\, InhR\, x\, ET\, x\, EF\, x\, ED}{BW\, x\, AT} \tag{1}$$

where ADD is the average daily dose of the pollutant (μg/kg/day); Cair is the concentration of pollutant in ambient air determined by dispersion modelling (μg/m^3); InhR is the inhalation rate (m^3/h); ET is the exposure time (h/day); EF is the exposure frequency (days/year); ED is the exposure duration (years); BW is the body weight of the exposed group (kg); AT is the averaging time (days). AT was calculated by the following Eq. (2):

$$AT = EDx365 \tag{2}$$

The ADD was calculated among different age groups, namely children (6–12 years) and general population of adults (19–75 years). The values of the parameters used to compute ADD are shown in Table 10.

The EF value of 241 days per year was used to calculate exposure of a person (child and adults) with the assumption that the entire population in the residential zone is exposed to NO_2 and CO pollutants during heating season from 1 September to 30 April. The ET value was assessed for whole day exposure to these pollutants.

The non-cancer risks of NO_2 and CO for the study population were estimated using the hazard quotient (HQ). According to Muller et al. [32], the HQ measures the presence or absence of adverse health effects due to exposure to a pollutant. It is defined by dividing the ADD from each exposure route by a definite reference dose (RfD) according to following Eq. (3):

Table 10 Values of parameters used in equations of the ADD

Parameter	Unit	Exposed group		References
		Child (6–12 years)	Adult (19–75 years)	
InhR	[m^3/day]	16.6	21.4	(U.S. [51]
EF	[days/year]	241	241	–
ED	[years]	12	30	–
AT	[days]	4,380	10,950	–
BW	[kg]	45.3	71.8	(U.S. [51]

$$HQ = \frac{ADD}{RfD} \tag{3}$$

where RfD is the maximum daily exposure limit allowable for humans.

According to World Health Organization [56], 24-h guideline mean value of 25 μg/m^3 was set to protect the public from the health effects of NO_2. Maximum CO daily 8-h mean within a calendar year is 10 mg/m^3 (European Parliament, Council of the European Union, 2008). The air quality standard of Japan sets a limit of 10 ppm (11.4 mg/m^3) to the average daily CO concentration [28]. Thus, we considered value of 11.4 mg/m^3 for the calculation of HQ.

An HQ of 1.0 is the benchmark of safety. An HQ that is $<$ 1.0 indicates an insignificant or negligible risk, and pollutant is not likely to induce adverse health effects, even to a sensitive individual. An HQ $>$ 1.0 indicates that there may be some levels of risks to sensitive individuals as a result of exposure (U.S. [53].

Results and discussion

Model validation

The AERMOD model is one of the most commonly studied and validated dispersion models in the world. Studies in this field have typically demonstrated good correlation with real observations. To validate the model's accuracy we followed the recommendations of the EPA's "Guideline on Air Quality Models" [54]. The accuracy of the model is normally determined by an evaluation procedure which involves the comparison of model concentration estimates with measured air quality data. The statement of model accuracy is based on statistical tests or performance measures, although a detailed analysis of these recommendations is beyond the scope of this paper.

Total amount of emissions comparison

Firstly, we focused on comparison of total amount of CO and NO_X pollutants produced by each heating scenario. The total amount of these pollutants was calculated for 5736 operating hours during heating season. As can be seen from Table 11, Scenario 1 produced much higher NO_X and CO pollutants than other two investigated scenarios. From these results it is clear that Scenario 3 reached approximately 53% of CO concentration values and even 82% of NO_X concentration values determined in Scenario 2.

Results in Table 11 showed that substitution of current heating system would importantly reduce yearly average amount of NO_X and CO. Although, it is necessary to note, that such a comparison is not entirely correct. Firstly, DHS in Scenario 1 also supplies heat to commercial sector in this locality, in particular to the neighbouring wood processing company. Therefore, the heat output of DHS significantly exceeds the heat demand required in Scenario 3. Installing of HWB would decrease total rated thermal input of the power plant, thus emissions of NO_X and CO will decrease as well. On the other hand, DHS also produces 843.95 t/year of sulfur dioxide (SO_2) and 45.02 t/year of particulate matter (PM) emissions due to biomass and lignite combustion, which were not taken into account in this study.

Ileri and Moshiri [22], studied fuel and heating system options in terms of energy consumption, pollutant emissions and economy in four Turkish cities. The authors compared several individual, central and district fuel and heating systems. Compared with present study, a seven floors apartment with fourteen apartments with 100 m^2 of heating area for each apartment was taken into account. From an environmental point of view, the authors considered carbon dioxide (CO_2) and SO_2 emissions. They concluded that lignite using systems as fuel source are the worst concerning environmental aspects. Replacing lignite with natural gas as an energy source would reduce CO_2 emissions to 6.18 t/year and SO_2 emissions would not be emitted at all. According to Landrigan et al. [24], natural gas combustion generates less CO_2 per unit of energy than combustion of coal and produces only negligible quantities of sulfur dioxide, mercury, and particulate matter (PM). Therefore, we did not consider SO_2 and PM emissions to compare investigated scenarios in our study.

Dispersion modelling results

Table 12 shows the descriptive statistics for estimated shortbterm (i.e., 1-h, 8-h, 24-h) and heating season average concentration values of NO_X expressed as NO_2 and CO pollutants from 441 receptors located at study domain.

The spatial distribution of NO_2 and CO concentration values in the study domain are shown in Fig. 5 and Fig. 6 on the basis of AERMOD dispersion model results.

The normal distribution of the data was evaluated utilizing the Shapiro–Wilk Test. The *p*-values obtained

Table 11 Comparison of total amount of produced pollutants by each heating scenario

Scenario	Building type	Emission rate		Number of modelled combustion units	Amount of pollutant	
		NO_X	CO		NO_X	CO
–	–	[t/h]	[t/h]	–	[t/year]	[t/year]
Scenario 1	–	1.03E-01	1.09E-02	1	589.96	62.57
Scenario 2	–	1.44E-03	2.52E-04	2	16.52	2.89
Scenario 3	Type A-3E	2.55E-05	6.91E-06	19	2.77	0.75
	Type A-2E	1.68E-05	4.57E-06	38	3.66	1.00
	Type B	8.50E-06	2.30E-06	25	1.22	0.33
	NRB	3.07E-05	8.32E-06	6	1.06	0.29

3E = building Type A with 3 entrances; 3E = building Type A with 2 entrances; NRB = non-residential building

Table 12 AERMOD dispersion modelling results within study domain based on descriptive statistics

Scenario	Pollutant	1-h/8-h Averaging period[a] [µg/m^3]			24-h Averaging period [µg/m^3]			Heating season average [µg/m^3]		
		Peak value	Mean ± SD	Median	Peak value	Mean ± SD	Median	Peak value	Mean ± SD	Median
1	NO_2	296.63	18.65 ± 30.62	13.54	23.82	3.08 ± 2.95	2.48	2.49	0.30 ± 0.29	0.23
	CO	5.92	0.79 ± 0.72	0.65	2.53	0.33 ± 0.31	0.26	0.26	0.03 ± 0.03	0.02
2	NO_2	81.24	8.15 ± 11.51	4.72	14.06	1.25 ± 1.39	0.78	0.81	0.11 ± 0.12	0.06
	CO	6.09	0.46 ± 0.58	0.29	2.46	0.22 ± 0.24	0.14	0.14	0.02 ± 0.02	0.01
3	NO_2	46.58	7.77 ± 7.34	5.84	8.02	1.16 ± 1.01	0.98	1.20	0.17 ± 0.19	0.11
	CO	4.61	0.67 ± 0.63	0.53	2.18	0.32 ± 0.28	0.27	0.33	0.05 ± 0.05	0.03

[a] 1-h averaging period for NO_2 concentrations; 8-h averaging period for CO concentrations

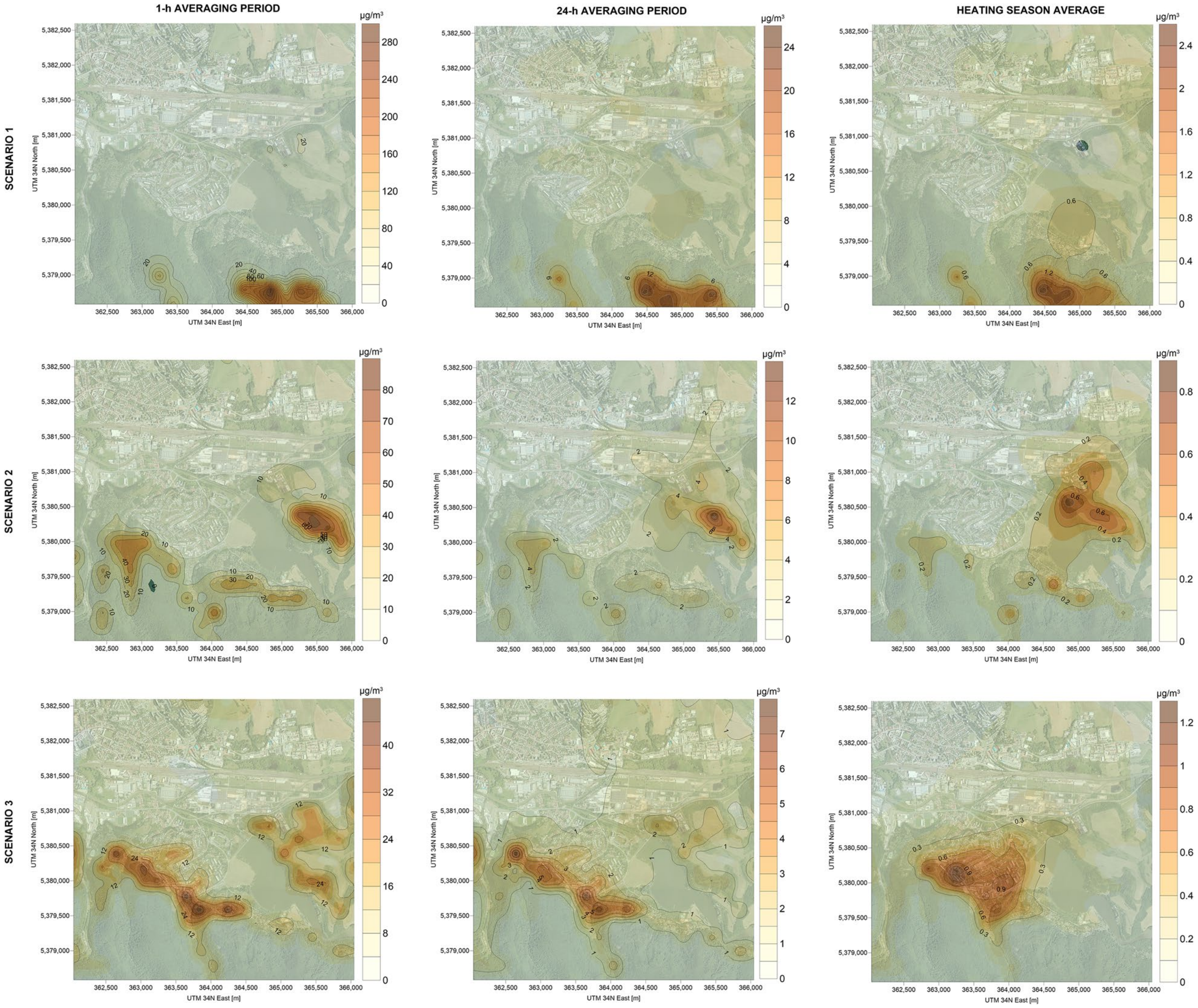

Fig. 5 Distribution of estimated 1-h, 24-h and heating season average NO_2 concentration values from investigated scenarios within study domain

from the Shapiro–Wilk Test were calculated for each investigated scenario and averaging period, revealing a significance level of $p \leq 0.001$. Consequently, it can be concluded that the data does not follow a normal distribution. Hence, a non-parametric Kruskal–Wallis test was conducted to investigate the difference among particular

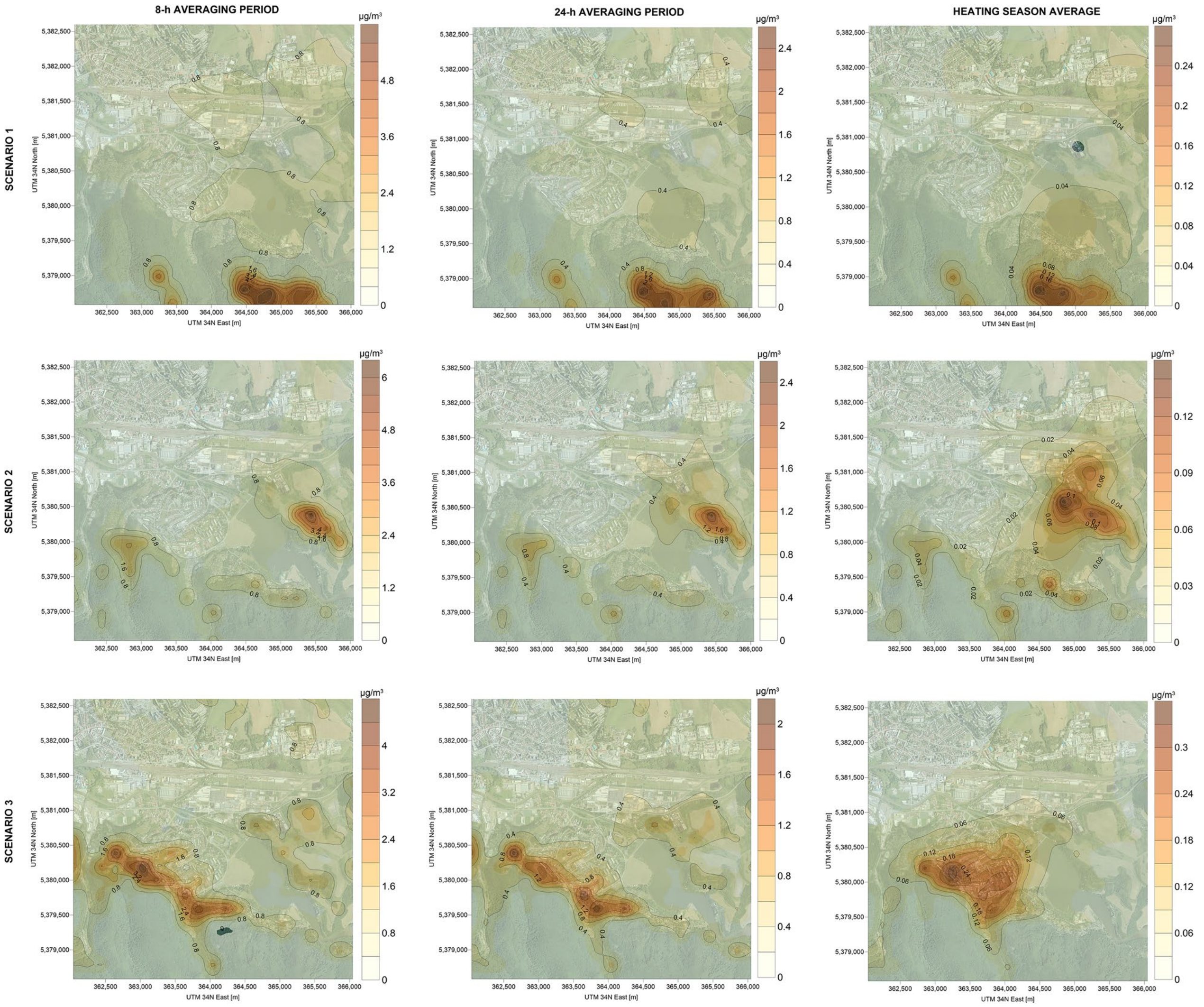

Fig. 6 Distribution of estimated 8-h, 24-h and heating season average CO concentration values from investigated scenarios within study domain

heating scenarios of modelled concentrations of pollutants. Post hoc analysis were based on Tukey's Honest Significant Difference test. All statistical analyses were carried out using JASP computer software version 0.17.0 (University of Amsterdam, Amsterdam, the Netherlands).

Table 13 shows Kruskal–Wallis Test and Post Hoc Tukey Test results for all investigated heating scenarios and averaging periods.

The distribution of the NO_2 and CO pollution plume in Scenario 1 follows the prevailing wind from north to south and peak concentrations for all investigated averaging periods were found at mountainous terrain (5,378,784.28N, 364,442.76E; 523.30 masl), approximately 2.03 km from the centre of the residential zone Zvolen-Sekier. Therefore, release height of the stack from current power plant provides appropriate dispersion of pollutants, despite numerous inverse situations in this locality and approximately 20% of calm wind situations during a year. This is in agreement with Holnicki and Nahorski [21], who concluded that the high stacks of plants in the district central heating system affect mainly the very distant receptors often situated outside the domain. The peak values of NO_2 and CO concentrations in present study referred to conditions of low wind speed (< 2 m/s), limited surface friction velocity, low temperature and atmospheric pressure, Monin–Obukhov length values typical of prevailing stable atmospheric conditions, and limited height of the mixed layer. Such conditions clarify the accumulation of pollutants in mountainous terrain.

In Scenario 2, the point of the peak concentration values was found in closer distance to the residential zone, nevertheless still outside its urban area at the distance of approximately 1.86 km (5,380,389.88N, 365,443.66E; 372.70 masl). In total, 8-h peak CO concentration in

Table 13 Kruskal–Wallis test and Post Hoc Tukey test results

Pollutant	Averaging period	Statistic	df	Kruskal–Wallis Test *p* value	Post hoc comparisons (Tukey Test) *p* value		
					S1 vs S2	S1 vs S3	S2 vs S3
CO	8-h	238.95	2	< 0.001	< 0.001	0.016	< 0.001
	24-h	132.60	2	< 0.001	< 0.001	0.823	< 0.001
	Heating season average	212.11	2	< 0.001	< 0.001	< 0.001	< 0.001
NO_2	1-h	469.87	2	< 0.001	< 0.001	< 0.001	0.955
	24-h	497.88	2	< 0.001	< 0.001	< 0.001	0.759
	Heating Season Average	327.11	2	< 0.001	< 0.001	< 0.001	< 0.001

The heating scenarios are marked with an abbreviation "S" in the table

Scenario 2 reached higher value than in Scenario 1, however, in general, determined CO concentrations at urban area receptors were lower. The Kruskal–Wallis Test followed by Tukey´s Post Hoc Test showed that there was statistically significant difference ($p < 0.001$) in determined CO concentrations for each averaging period between Scenario 1 and Scenario 2. On the other hand, by comparing Scenario 1 and Scenario 3 we found no statistically significant difference ($p = 0.823$) among 24-h averaging period CO concentration values. Interestingly, 8-h averaging period CO concentrations were statistically significantly ($p < 0.01$) higher in Scenario 1 than Scenario 3, and on contrary heating season average CO concentrations were statistically significantly ($p < 0.001$) lower. By comparing Scenario 2 and Scenario 3 we found statistically significant difference ($p < 0.001$) in all investigated averaging periods of CO concentrations, and higher values were reached by Scenario 3.

Scenario 1 reached significantly ($p < 0.001$) higher NO_2 concentration values compared to Scenario 2, as well as, Scenario 3 in all modelled averaging periods. Among 1-h and 24-h NO_2 concentration values in Scenario 2 and Scenario 3 were not found statistically significant ($p = 0.955$ and $p = 0.759$, respectively) differences. On the other hand, heating season average NO_2 concentration values were statistically significantly ($p < 0.001$) higher in Scenario 3 compering to Scenario 2.

It is also important to highlight the fact that peak values of NO_2 and CO concentrations in Scenario 3 were located directly in the residential zone (363,041.50N; 5,380,189.18E, 345.70 masl) which is in agreement with Holnicki and Nahorski [21], who stated that small point sources of individual heating systems are mainly active in suburban districts.

Therefore, we conducted the statistical comparison of modelled data solely at residential zone domain which was approximately equal to its urban area with following boundaries expressed in meters as UTM 34N (X;Y) coordinates: 362,040.60E (X_{min}), 366,044.20E (X_{max}), 5,378,583.58N (Y_{min}) and 5,382,597.58N (Y_{max}). Ground-level CO and NO_2 concentration values at urban residential zone are compared in Fig. 7.

Figure 7 shows raincloud plots comparing each heating scenario of NO_2 modelled concentrations in urban area of residential zone. Some differences can be noticed: in general, we found a decrease in mean NO_2 ground-level concentration for Scenario 2 and Scenario 3, however, more variable ranges of pollutants concentrations with markedly higher peak values compared to Scenario 1. Contrary to the data presented in Table 12, short-term 1-h and 24-h peak NO_2 concentrations in Scenario 2 and Scenario 3 were 53.05 and 46.58 μg/m^3, respectively. Thus, which were much higher values compared to Scenario 1 (12.25 and 2.13 μg/m^3). In contrast, mean 1-h and 24-h NO_2 concentration values in Scenario 2 were 8.93 and 1.23 μg/m^3, respectively. Results show that fuel base substation in Scenario 2 would reduce average concentrations of NO_2 and CO up to 0.09 μg/m^3.

Interestingly, only in heating season average period, the assumption that the highest ground-level NO_2 concentration will be produced in Scenario 3 has already been fulfilled. Specific values for this averaging period and investigated scenarios were 2.28, 1.22 and 2.13 μg/m^3, respectively.

As can be seen in Fig. 7, in all investigated averaging periods we determined higher ranges, as well as, peak values of CO concentrations in Scenario 3 within urban residential zone. The differences of mean values among Scenario 3 compared to Scenario 1 and Scenario 2 were significant ($p < 0.001$). However, it is important to highlight the fact that all modelled 8-h CO concentration values were far below the WHO air quality guideline limit value set at 10 mg/m^3. No limit value is set for 24-h and average CO concentrations. Thus, in the evaluation of CO averaging periods we focused primarily on the peak values to which members of the public can be exposed. Calculated 8-h CO peak value (4.61 μg/m^3) in Scenario 3 within residential zone was identical with data showed in

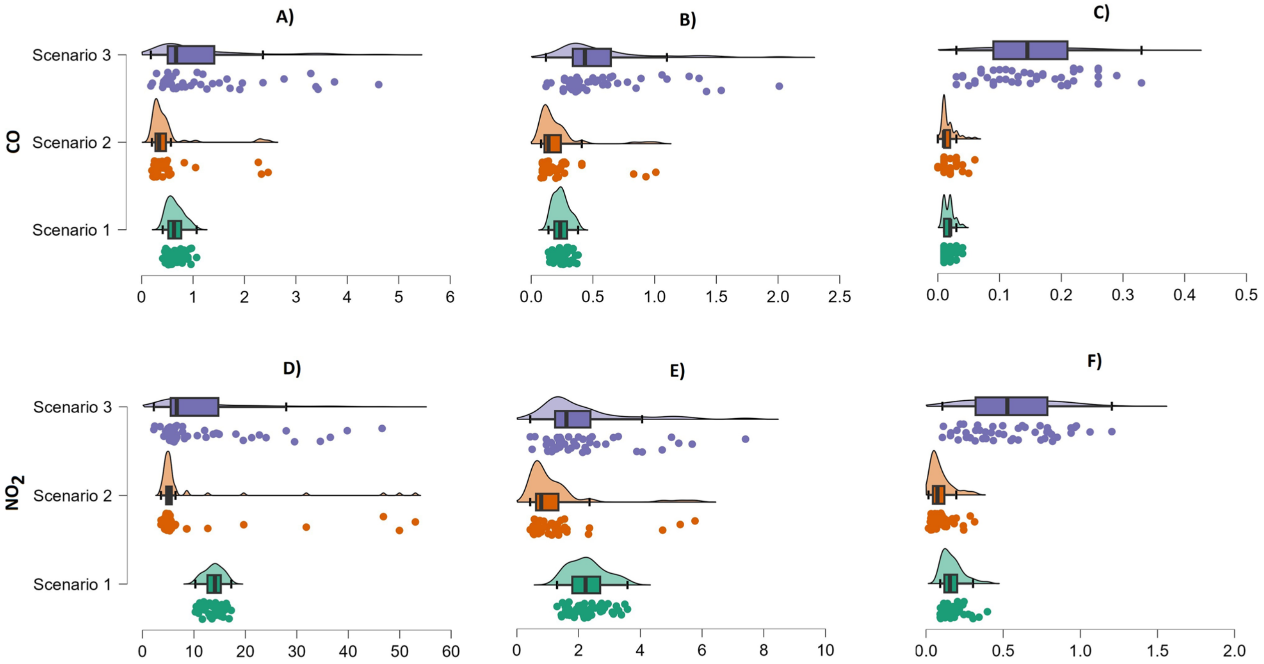

Fig. 7 Raincloud plots comparing each heating scenario of CO and NO_2 ground-level concentrations (μg/m.^{3}) at urban residential zone: **A** CO 8-h concentrations; **B** CO 24-h concentrations; **C** CO heating season average concentrations; **D** NO_2 1-h concentrations; **E** NO_2 24-h concentrations; **F** NO_2 heating season average concentrations. Plot created in JASP computer software version 0.17.0 (University of Amsterdam, Amsterdam, the Netherlands)

Table 12 (AERMOD dispersion modelling results within study domain). On the other hand, the flue gas parameters and release conditions investigated in Scenario 1 and Scenario 2 caused that 8-h CO peak values within urban residential zone decreased compared with whole study domain approximately 69% and 60%, respectively. The decrease at the level of peak 24-h and average concentration values within urban residential zone were approximately 84% and 60% both in Scenario 2 and Scenario 3.

By comparing mean value of all computed receptors at urban residential zone for 8-h averaging period in investigated Scenario 1, Scenario 2 and Scenario 3 we found 0.66, 0.50 and 1.19 μg/m^3, respectively. Therefore, disconnection of apartment buildings and non-residential buildings from DHS leads to an increase in CO ground concentration.

Presence of several individual heating systems with small amount of emission release huge amount of pollutans concentrations located close to high-rise. A similar pattern of results was obtained in study conducted by Aristodemou et al. [3], who concluded that presence of tall buildings leads to pollution remaining locally within the residential area. In investigated residential zone Zvolen-Sekier, tall buildings predominate over low ground floor buildings.

Several guidelines on air quality models state that the modelling domain must be large enough so that the AERMOD receptor network will be both sufficiently detailed and extensive enough so as to fully represent the immediate surrounding terrain and the entire domain being modeled. It is also important to highlight the fact that the domain size states that the digital elevation model array and domain boundary of a model must include all terrain features that exceed a 10% elevation slope from any given receptor (U.S. [49]. The 10% slope rule may lead to excessively large domains in areas with considerable terrain features which is the case of present study. In addition, according to Pantusheva et al. [36], close to 20% of reviewed papers aimed on air dispersion modelling did not follow the established recommendations in terms of computational domain size. The domain size in present study was carefully chosen and properly described for eventual reproduction of the study. From the results, it is clear that domain size and receptors location must be chosen with respect to the conditions of the evaluated area and the same approach must be taken to evaluate the results of pollutant concentrations.

Human health risk of NO_2 and CO pollutants

The ADD and HQ was used for the estimation of non-carcinogenic risks to human health that derive from NO_2

and CO from investigated scenarios of heating systems in residential zone Zvolen-Sekier. The HQ was calculated by Eq. (3) based on the AERMOD results of 24-h averaging period NO_2 and CO concentrations. The ADD and HQ were calculated for each heating scenario at 48 receptors located directly in the residential zone. Table 14 shows computed mean values of ADD and HQ for exposed group of adults and children.

The results for all HQ values deriving from exposure to NO_2 and CO via the inhalation pathway were less than 1.0 for each heating scenario, which indicates the existence of a low hazard. Scenario 3 can be considered as the least appropriate option of heating supply for investigated residential zone due to slightly higher values of HQ compared with other two scenarios both for NO_2 and CO pollutants. The ADD and HQ values in relation to children were higher than those for general population of adults, but still relatively low in overall. Nevertheless, several studies have established that exposure to especially low concentrations of NO_2 may increase the risks of asthma, respiratory diseases, pneumonia or decreased lung function especially in children [6, 20, 31, 33]. Therefore, any contribution to increasing NO_2 concentrations is not desirable. According to Morakinyo et al. [30], infants and children, are more likely to be affected rather than adults by the exposure to pollutants via inhalation. Moreover, Zhang et al. [57] concluded that an increase of NO_2 concentrations in 10 μg/m^3 leads to an increase of 1.3% in hospital admissions associated with pulmonary diseases and 2.6% in mortality.

Conclusion

The aim of the present study was to evaluate the effects of different heating systems scenarios not from an economic point of view, but from the perspective of the impact on air quality and human health, as this aspect is often neglected. The findings of this study improve our knowledge about the atmospheric pollution that would be generated by massive disconnection of residential zone from district heating system.

When considering the entire study domain, it can generally be stated for all averaged periods that the current heating supply in residential zone provided by district heating system is the most unfavorable variant for the maximum calculated values of NO_2 and CO concentrations. On the other hand, by the spatial analysis of pollutants distribution, the most affected receptors were found outside the urban residential zone. Results of air dispersion modelling via AERMOD showed that the height of the stack from current district heating system plant provides appropriate dispersion of pollutants, despite numerous inverse and calm wind situations in Zvolenská Kotlina basin, which is considered to be the basin with the most frequent occurrence of inverse situations in Slovakia. Under these circumstances, it can be concluded that the air dispersion modelling was carried out under the worst-case conditions and this study can serve as a model for similar situations in other locations. In addition, our results demonstrated that air dispersion reports can be affected by uncertainty if the computational domain is chosen incorrectly.

Substitution of the fuel base in district heating system would not cause a significant change in terms of the spatial distribution of NO_2 and CO concentrations, however, we guess the quantity of these pollutatns would be reduced. The disconnection of heat consumers from the district heating system would lead to redistribution of pollutants to the area of the own residential zone with the presence of hygienically protected buildings such as schools or medical facilities. At the same time, there would be an increase in peak NO_2 and CO concentrations compared to the current state.

Moreover, all investigated Scenarios showed low hazard quotient value according to human health risk assessment, however, individual heating system is considered more risky, especially in infants and children population. Therefore, the individual heating systems contribute additional source of pollution in residential zone increasing several health diseases and adverse environmental condition compared to district heating systems, which also have added value such as heat supply for industry and production of electricity from steam.

Many complex factors interact in the process of transport of pollutans in the atmosphere, and this study has some limitations. During the transport of air pollutants, the building downwash effect is such a factor, however, a detailed understanding of the mechanism underlying its influence at the scale of whole residential zone is lacking due to simplification of the model based on the average apartment building. In future, more comprehensive study is needed, to analyze this limitation.

Table 14 ADD and HQ values for NO_2 and CO at investigated urban residential zone

Scenario	Pollutant	Child (6–12 years)		Adult (19–75 years)	
		ADD [μg/kg/day]	HQ -	ADD [μg/kg/day]	HQ –
1	NO_2	0.55	0.02	0.45	0.02
	CO	0.06	5.00E-06	0.05	4.00E-06
2	NO_2	0.30	0.01	0.24	9.66E-03
	CO	0.05	5.00E-06	0.04	4.00E-06
3	NO_2	0.52	0.02	0.42	0.02
	CO	0.14	1.23E-05	0.11	1.00E-05

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12302-023-00798-1.

Additional file1: Figure S1. Position of modelled sources of emissions in residential area Zvolen–Sekier. **Table S1.** Detailed input data for AERMOD dispersion model in Scenario 3 (AERMOD View—Source Parameters, MS Excel - Lakes Format: Version 2.0). **Table S2.** AERMOD dispersion modelling results at urban residential area

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Author contributions

JS and JP wrote the main manuscript text. OR and MS performed the scenarios. MV prepared tables with parameters. MS prepared figures. All authors reviewed the manuscript.

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Availability of data and materials

The authors confirm that the data supporting the findings of this study are available within the article [and/or] its supplementary materials.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Consent to publish was obtained from all individual participants included in the study.

Competing interests

The authors have no relevant competing interests to disclose.

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References

1. Aliyu AS (2015) Assessment of potential human health and environmental impacts of a nuclear power plant (NPP) based on atmospheric dispersion modeling. Atmósfera 28:13–26
2. Antimonopoly Office of the Slovak Republic, 2013. Operation and problems in the heat management sector in the Slovak Republic with a focus on DHS from the perspective of the Antimonopoly Office of the Slovak Republic (Research report). Bratislava. https://www.antimon.gov.sk/fungovaniea- problemy-v-sektore-tepelneho-hospodarstva-sr-so-zameranim-na-systemy-czt-z-pohladuprotimonopolneho- uradu-sr/?undefined=undefined
3. Aristodemou E, Boganegra LM, Mottet L, Pavlidis D, Constantinou A, Pain C, Robins A, ApSimon H (2018) How tall buildings affect turbulent air flows and dispersion of pollution within a neighbourhood. Environ Pollut 233:782–796. https://doi.org/10.1016/j.envpol.2017.10.041
4. Baykara M, Im U, Unal A (2019) Evaluation of impact of residential heating on air quality of megacity Istanbul by CMAQ. Sci Total Environ 651:1688–1697. https://doi.org/10.1016/j.scitotenv.2018.10.091
5. Braniš M, Domasová M, Řezáčová P (2007) Particulate air pollution in a small settlement: the effect of local heating. Appl Geochem 22:1255–1264. https://doi.org/10.1016/j.apgeochem.2007.03.016
6. Cibella F, Cuttitta G, Della Maggiore R, Ruggieri S, Panunzi S, De Gaetano A, Bucchieri S, Drago G, Melis MR, La Grutta S, Viegi G (2015) Effect of indoor nitrogen dioxide on lung function in urban environment. Environ Res 138:8–16. https://doi.org/10.1016/j.envres.2015.01.023
7. Dunkerley F, Spanton AM, Hall DJ, Bennett M, Griffiths RF 2001. An Intercomparison of the AERMOD, ADMS and ISC Dispersion Models for Regulatory Applications: Dispersion over Terrain. The 7th International Conference on Harmonization within Atmospheric Dispersion Modelling for Regulatory Purposes, 28–31 May, 2001, Belgirate, Italy
8. European Parliament, Council of the European Union, (2008) Directive 2008/50/EC of the European Parliament and of the Council of 21 May 2008 on ambient air quality and cleaner air for Europe, OJ L. https://link.springer.com/article/10.1007/s00038-017-0952-y
9. Farr TG, Rosen PA, Caro E, Crippen R, Duren R, Hensley S, Kobrick M, Paller M, Rodriguez E, Roth L, Seal D, Shaffer S, Shimada J, Umland J, Werner M, Oskin M, Burbank D, Alsdorf D (2007) The shuttle radar topography mission. Rev Geophys. https://doi.org/10.1029/2005RG000183
10. Fleming ZL, Paul S. Monks, Alistair JM (2012) Untangling the influence of air-mass history in interpreting observed atmospheric composition. Atmos Res 104–105:1–39
11. Gulia S, Kumar A, Khare M (2015) Performance evaluation of CALPUFF and AERMOD dispersion models for air quality assessment of an industrial complex. J Sci Ind Res 74(5):302–307
12. Gibson MD, Kundu S, Satish M (2013) Dispersion model evaluation of PM2.5, NOx and SO2 from point and major line sources in Nova Scotia, Canada using AERMOD gaussian plume air dispersion model. Atmos Pollut Res 4:157–167. https://doi.org/10.5094/APR.2013.016
13. Goričanec D, Ivanovski I, Krope J, Urbancl D (2020) The exploitation of low-temperature hot water boiler sources with high-temperature heat pump integration. Energies 13:6311. https://doi.org/10.3390/en13236311
14. Guzzini A, Pellegrini M, Pelliconi E, Saccani C (2020) Low temperature district heating: an expert opinion survey. Energies 13:810. https://doi.org/10.3390/en13040810
15. Gulia S, Kumar A, Khare M (2015) Performance evaluation of CALPUFF and AERMOD dispersion models for air quality assessment of an industrial complex. J Sci Ind Res 74:302–307. http://nopr.niscair.res.in/bitstream/123456789/31451/1/JSIR%2074%285%29%20302-307.pdf
16. Hanna SR, Egan BA, Purdum J, Wagler J (2001) Evaluation of the ADMS, AERMOD, and ISC3 dispersion models with the OPTEX, Duke Forest, Kincaid, Indianapolis and Lovett field datasets. Int. J. Environment and Pollution 16(1–6):301–314. https://doi.org/10.1504/IJEP.2001.000626
17. Hall DJ, Spanton AM, Bennett M, Dunkerley FN, Griffiths RF, Fisher BEA, Timmis RJ, (2000) An inter-comparison of the AERMOD, ADMS and ISC dispersion models for regulatory applications. UK Environment Agency, R&D Technical Report P362. https://link.springer.com/chapter/10.1007/0-306-47813- 7_44
18. Hansen CH, Gudmundsson O (2018) The competitiveness of district heating compared to individual heating: When is district heating the cheapest source of heating? Green Energy Association. https://lsta.lt/wp-content/uploads/2019/04/EU-DH-vs-IND-heating-03052018-The-competitiveness-of-districtheating- compared-to-individual-heatingv2.pdf
19. Harsham KD, Bennett M (2008) A Sensitivity Study of the Validation of Three Regulatory Dispersion Models. Environ Sci 4(1):63–76
20. He B, Huang JV, Kwok MK, Au Yeung SL, Hui LL, Li AM, Leung GM, Schooling CM (2019) The association of early-life exposure to air pollution with lung function at ~17.5 years in the "Children of 1997" Hong Kong Chinese Birth Cohort. Environ Int 123:444–450. https://doi.org/10.1016/j.envint.2018.11.073
21. Holnicki P, Nahorski Z (2015) Emission data uncertainty in urban air quality modeling—case study. Environ Model Assess 20:583–597. https://doi.org/10.1007/s10666-015-9445-7
22. Ileri A, Moshiri S (1996) Effects of common fuel and heating system options on the energy usage, pollutant emissions and economy. Energy Build 24:11–18. https://doi.org/10.1016/0378-7788(95)00960-4
23. Kaczmarczyk M, Sowizdzal A, Tomaszewska B (2020) Energetic and environmental aspects of individual heat generation for sustainable development at a local scale—a case study from Poland. Energies 13(2):454. https://doi.org/10.3390/en13020454

24. Landrigan PJ, Frumkin H, Lundberg BE (2020) The false promise of natural gas. N Engl J Med 382:104–107. https://doi.org/10.1056/NEJMp1913663
25. Lazzarin R (2020) Heat pumps and solar energy: a review with some insights in the future. Int J Refrig 116:146–160. https://doi.org/10.1016/j.ijrefrig.2020.03.031
26. Mateusz R (2019) Parameterization and evaluation of the CALMET/CALPUFF model system in near-field and complex terrain—Terrain data, grid resolution and terrain adjustment method. Sci Total Environ 689:31–46
27. Búš, V. Zásahy do nosných konštrukcií panelových bytových domov. MVRR SR, 2. vydanie. Bratislava, 2008. ISBN 978-80-89073-14-6
28. Ministry of the Environment Government of Japan, 2023. Environmental quality standards in japan - Air Quality [WWW Document]. Ministry of the Environment, Government of Japan. URL https://www.env.go.jp/en/air/aq/aq.html. Accessed 1 Jan 2023
29. Ministry of Transport and Construction of the Slovak Republic (2008). Interventions in Load-Bearing Structures of Prefabricated Apartment Buildings, 2nd ed. Ústav vzdelávania a služieb, s.r.o., Bratislava
30. Morakinyo OM, Adebowale AS, Mokgobu MI, Mukhola MS (2017) Health risk of inhalation exposure to sub-10 µm particulate matter and gaseous pollutants in an urban-industrial area in South Africa: an ecological study. BMJ Open 7:e013941. https://doi.org/10.1136/bmjopen-2016-013941
31. Mudway IS, Dundas I, Wood HE, Marlin N, Jamaludin JB, Bremner SA, Cross L, Grieve A, Nanzer A, Barratt BM, Beevers S, Dajnak D, Fuller GW, Font A, Colligan G, Sheikh A, Walton R, Grigg J, Kelly FJ, Lee TH, Griffiths CJ (2019) Impact of London's low emission zone on air quality and children's respiratory health: a sequential annual cross-sectional study. Lancet Public Health 4:e28–e40. https://doi.org/10.1016/S2468-2667(18)30202-0
32. Muller E, Diab RD, Binedell M, Hounsome R (2003) Health risk assessment of kerosene usage in an informal settlement in Durban, South Africa. Atmos Environ 37:2015–2022. https://doi.org/10.1016/S1352-2310(03)00125-0
33. Nhung NTT, Schindler C, Dien TM, Probst-Hensch N, Perez L, Künzli N (2018) Acute effects of ambient air pollution on lower respiratory infections in Hanoi children: an eight-year time series study. Environ Int 110:139–148. https://doi.org/10.1016/j.envint.2017.10.024
34. Olufemi AC, Mji A, Mukhola MS (2019) Health risks of exposure to air pollutants among students in schools in the vicinities of coal mines. Energy Explor Exploit 37:1638–1656. https://doi.org/10.1177/0144598718765489
35. Pandey G, Venkatram A, Arunachalam S (2023) Evaluating AERMOD with measurements from a major U.S. airport located on a shoreline. Atmos Environ. https://doi.org/10.1016/j.atmosenv.2022.119506
36. Pantusheva M, Mitkov R, Hristov PO, Petrova-Antonova D (2022) Air pollution dispersion modelling in urban environment using CFD: a systematic review. Atmos 13:1640. https://doi.org/10.3390/atmos13101640
37. Perry SG, Cimorelli AJ, Paine RJ, Brode RW, Weil JC, Venkatram A, Wilson RB, Lee RF, Peters WD (2005) AERMOD: a dispersion model for industrial source applications. part II: model performance against 17 field study databases. J Appl Meteorol Climatol 44:694–708. https://doi.org/10.1175/JAM2228.1
38. Poputoaia D, Bouzarovski S (2010) Regulating district heating in Romania: Legislative challenges and energy efficiency barriers. Energy Policy 38:3820–3829. https://doi.org/10.1016/j.enpol.2010.03.002
39. Pozzi M, Spirito G, Fattori F, Dénarié A, Famiglietti J, Motta M (2021) Synergies between buildings retrofit and district heating. The role of DH in a decarbonized scenario for the city of Milano. Energy Rep 7:449–457. https://doi.org/10.1016/j.egyr.2021.08.083
40. Riddle A, Carruthers D, Sharpe A, McHugh C, Stocker J (2004) Comparisons between FLUENT and ADMS for atmospheric dispersion modelling. Atmos Environ 38(7):1029–1038
41. Sidle C, Tuckett-Jones B, Ng B, Shi JP 2002 Model Intercomparison between ADMS 3.1 and AERMOD and AERMOD PRIME, paper presented at the 9th Int. Conf. on Harmonization within Atmospheric Dispersion Modelling for Regulatory Purposes, 1–4 June 2004, Germany: Garmisch-Partenkirchen
42. Slámová M, Beláček B, Chudý F (2015) Natural Limits of the Settlement Growth in the Carpathian Neogene Basin (the town of Zvolen, Slovakia), in: Environment and Ecology at the Beginning of 21st Century, 1st Ed. St. Kliment Ohridski University Press Sofia, pp. 570–589
43. Slovak Hydrometeorological Institute 2021. Air Pollution in the Slovak Republic—2020. Air quality department. Slovakia: Bratislava
44. Slovak Innovation and Energy Agency (2022) Expertly on energy [WWW Document]. URL https://www.siea.sk/odborne-o-energii/. Accessed 1 Jan 2022
45. Statistical Office of the Slovak Republic(2022). Demographic and social statistics
46. Steven RH, Bruce AE, John P, Jen W (2001) Evaluation of the ADMS, AERMOD, and ISC3 dispersion models with the OPTEX, Duke forest, kincaid, indianapolis and lovett field datasets. Int J Environ Pollut 16(1–6):301–14
47. Tartakovsky D, Broday DM, Stern E (2013) Evaluation of AERMOD and CALPUFF for predicting ambient concentrations of total suspended particulate matter (TSP) emissions from a quarry in complex terrain. Environ Pollut 179:138–145
48. Till JE, Rood AS, Garzon CD, Lagdon RHJ (2014) Comparison of the MACCS2 atmospheric transport model with lagrangian puff models as applied to deterministic and probabilistic safety analysis. Health Phys 107(3):213–230
49. U.S. EPA 2019a. User's Guide for the AERMOD Terrain Preprocessor (AERMAP). U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Air Quality Assessment Division, Air Quality Modeling Group, North Carolina, NC, USA.
50. U.S. EPA 2019b. User's Guide for AERMOD Meteorological Preprocessor (AERMET). U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Air Quality Assessment Division, Air Quality Modeling Group, North Carolina, NC, USA.
51. U.S. EPA, 2011. Exposure Factors Handbook. Office of Research and Development's National Center for Environmental Assessments, Washington, D.C., USA.
52. U.S. EPA, 1992. Exposure Assessment Tools by Routes - Inhalation. Office of Emergency and Remedial Response, Washington, D.C., USA.
53. U.S. EPA, 1989. Risk Assessment Guidance for Superfund, Vol 1: Human Health Evaluation Manual (Part A). Office of Emergency and Remedial Response, Washington, D.C., USA.
54. U.S. EPA (2017). Revisions to the Guideline on Air Quality Models: Enhancements to the AERMOD Dispersion Modeling System and Incorporation of Approaches to Address Ozone and Fine Particulate Matter; Final Rule. 40 CFR Part 51; Federal Register: Washington, DC, USA;Volume 82, pp. 5182–5235
55. Wissner M (2014) Regulation of district-heating systems. Utilities Policy 31:63–73. https://doi.org/10.1016/j.jup.2014.09.001
56. World Health Organization, 2022. Ambient (outdoor) air pollution [WWW Document]. URL https://www.who.int/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health. Accessed 12 Dec 2022).
57. Zhang Z, Wang J, Lu W (2018) Exposure to nitrogen dioxide and chronic obstructive pulmonary disease (COPD) in adults: a systematic review and meta-analysis. Environ Sci Pollut Res Int 25:15133–15145. https://doi.org/10.1007/s11356-018-1629-7

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