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The Impact of Solid Fuel Residential Boilers Exchange on Particulate Matter Air Pollution

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Abstract: Combustion processes, including the use of solid fuels for residential heating, are a widespread custom for many households. Residential heating is a significant source of ambient air pollution, yet it varies greatly by geography, meteorologic conditions, the prevalence of the type of solid fuel and the technologies used. This study evaluates whether residential heating affects the air quality through modelling three given scenarios of solid fuel boiler exchange at selected locations and comparing the results with measured data. The findings of this study suggest that according to the modelled data, the main air pollution contributor is residential heating since Dolni Lhota (daily average of PM_{10} = 44.13 $\mu g \cdot m^{-3}$) and Kravare (daily average of PM_{10} = 43.98 $\mu g \cdot m^{-3}$) are locations with no industry in contrast to heavily industrial Vratimov (daily average of PM_{10} = 34.38 $\mu g \cdot m^{-3}$), which were modelled for the heating season situation. Nevertheless, actual measurements of PM_{10} during the same period suggest that the average levels of air pollution were significantly higher than the modelled values for Dolni Lhota by 64% and for Kravare by 51%. Thus, it was assumed that PM long-range or/and transboundary transports were involved.

Keywords: residential heating; boiler; air pollution; PM_{10}; dispersion model; long-range transport

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1. Introduction

The use of solid fuels for residential heating is still a common practice for households despite the extensive availability of electricity and natural gas. Solid fuels for heating comprise mainly wood and coal, as well as forestry and agricultural residues, and even municipal waste [1]. These materials continue to be used for residential cooking and heating by nearly 3 billion people worldwide at least part of the year, mostly during the winter months [2]. Combustion processes, including residential heating with wood and coal, are a significant source of ambient air pollution, yet it varies greatly by geography, the prevalence of the type of solid fuel and the technologies used. Evidence links emissions from wood and coal heating to serious health effects, such as respiratory and cardiovascular mortality, premature death and morbidity [3]. Wood and coal burning also emit carcinogenic compounds [4]. Each year, 61,000 premature deaths are attributable to ambient air pollution from residential heating with wood and coal in Europe [5]. The concentrations of PM in the winter are usually higher than in the summer, especially due to the heating season in winter and the combustion of solid fuels for household (residential) heating. Moreover, the winter concentrations can be much higher in smog episodes [6]. Total emissions of PM_{10} in the EU-28 decreased by 28.79% between 2000 and 2018. However, the PM_{10} emissions from households and the institutional and commercial building sectors have only decreased in this period by 13% [7].

The major problem with the burning of solid fuels is that the devices used for household heating incompletely combust the fuel causing their low combustion temperature and other limitations. This results in producing relatively high emissions of incomplete combustion per unit of fuel, such as primary particulate matter (PM_{10} and $PM_{2.5}$) and carbon monoxide (CO)—major air pollutants. Furthermore, black carbon (BC) emissions (a component of $PM_{2.5}$) can evolve during small-scale solid fuel combustion, causing climate warming [8]. By 2020, residential wood burning in Europe will become the dominant source of $PM_{2.5}$ [9]. When using coal for residential heating, additional emissions are produced, such as sulfur and other toxic contaminants found in some types of coal [10]. Nevertheless, household-level emission controls or regulations are often lacking. The recommendations on PM emission limit values for residential combustion installations with a rated capacity of less than 500 kW hours are given in the 1999 Gothenburg Protocol under the Convention on Long-Range Transboundary Air Pollution. The recommended emission limit values for PM depend on the type of fuel (wood: 75 mg/m^3; wood logs: 40 mg/m^3; pellets and other solid fuels: 50 mg/m^3) [11].

In most countries, there are regulatory measures available to reduce solid fuel emissions for residential heating. Principally, they encourage fuel switching (away from coal and other solid fuels), the use of more efficient combustion technologies (e.g., automatic feeder pellet stoves or certified fireplaces), the introduction of district heating and in-home high-efficiency particulate air (HEPA) filtration, which all lead to the reduction of emissions [12]. Existing regulatory measures include Commission Regulation (EU) 2015/1189 implementing Directive 2009/125/EC regarding ecodesign requirements for solid fuel boilers and Regulation (EU) 2015/1187 supplementing Directive 2010/30/EU with regard to energy labelling of solid fuel boilers and packages of a solid fuel boiler, supplementary heaters, temperature controls and solar devices. The limit values of ecodesign requirements for PM emissions, valid from the 1 January 2020, are 40 mg/m^3 (automatically stoked boilers) and 60 mg/m^3 (manually stoked boilers), which are mandatory for all manufacturers and suppliers in the EU countries [13]. These values are equivalent to the class 5 requirements specified in the EN303-5:2012. This norm specifies five classes for solid fuel boilers, with class 5 being the strictest. From the 1 January 2020, it is also only possible to buy boilers meeting the requirements of class 5. From the 1 January 2022, the use of class 1 and class 2 boilers will be banned.

With the implementation of new regulations and stricter requirements for emitted emissions (especially PM), national governments must prepare heater exchange guidelines. Mostly, these regulations will be effectively fulfilled if financial compensation is offered to assist with the cost of replacing old heaters with those meeting tight energy efficiency or emission limit regulations. More financial support for households can be achieved through a variety of environmental programs and campaigns [14].

Methods for obtaining air pollution information play an important role in the environmental field, regardless of their ongoing development. Both measurement and modelling are commonly used techniques for air pollution evaluation. Advantages and disadvantages of these techniques depend on the pollution sources, compounds and applications [15]. Air pollution modelling methods have gained a significant growth of interest in the last decade. Modelling tools are used in atmospheric dispersion models and can be used to estimate concentrations of air pollutants at potentially any number of locations in time and space. However, the majority of current dispersion models do not include a spatial analysis component or spatial interpretation of results. The use of GIS data in air pollution assessment makes the dispersion modelling more precise, and the results can be interpreted in a global perspective, e.g., the most widely used Gaussian dispersion model, such as SYMOS [16] and AERMOD [17]; a grid-based model, such as the Intervention Model for Air Pollution (InMAP) [18]; or a trajectory-based model such as the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model [19]. Transboundary air pollution is a global problem, especially in areas with a dense population. To simulate the transboundary air pollution and describe the dispersion of air pollutants, models can be used to target the potential source regions and the transboundary transport ways in a set time frame with given meteorological conditions [20].

The objective of this study was to evaluate whether residential heating affects the air quality through modelling three given scenarios of solid fuel boiler exchange at selected locations and comparing the results with measured data. Data for this study were obtained in a highly polluted area (Moravia-Silesia Region in the Czech Republic). The novelty of this research was identified in the field of the long-range air pollution transport pathways, as there exist only a few studies on this topic. When modelled and measured PM concentrations were compared, a significant contribution of long-range transport to particulate matter load was quantified for the two nonindustrial sites, whereas an industrial location remained intact by the long-range transport.

2. Materials and Methods

2.1. Locations

For this study, three areas were selected of different population, size and topographic relief. All the areas are located in the Moravian-Silesian region in the southeast part of the Czech Republic. The geographical position of the Moravian-Silesian region and selected locations can be seen in Figure 1. This region borders Poland and Slovakia. It is an area traditionally known as a coal-mining region (some of the mines are still in operation) with heavy industry (coking plants, steel plants and other metallurgical production), developed automotive production and substantial motor vehicle traffic.

- Dolni Lhota (CZ, the coordinates are Lat 49°50′31.776″ N Long 18°5′31.488″ E). This village is located near the city of Ostrava with approximately 1500 residents (area 5.36 km^2). It is spread over a hilly terrain, which has a significant impact on the emission stratification during the heating season. There is no heavy industry near the village; local heating and traffic are the main contributors to air pollution. The number of boilers replaced during the "boiler exchange campaign" in the Czech Republic was average in comparison with the other towns in the county (68% of boilers replaced). The number of houses with solid fuel boilers—67 units; the number of replaced solid fuel boilers—46 units.
- Kravare (CZ, the coordinates are Lat 49°55′55.308″ N Long 18°0′17.028″ E). This small town has a population of approximately 6700 residents across an area of 19.37 km^2. The terrain around the city is flat. There is no heavy industry near the village; local heating and traffic are the main contributors to air pollution. This town is geographically nearest to the Polish borders from the selected locations. The number of boilers replaced during the "boiler exchange campaign" in the Czech Republic was high in comparison with the other towns in the county (89% of boilers replaced). The number of houses with solid fuel boilers—252 units; the number of replaced solid fuel boilers—225 units.
- Vratimov (CZ, the coordinates are Lat 49°46′11.208″ N Long 18°18′37.944″ E). This town has a population of approximately 7300 residents across an area of 14.14 km^2. The topography of the town is characteristic of its undulating relief. There is a large steel plant (Liberty Ostrava), an industrial zone with lighter industries and a highway in close proximity to the city. The number of boilers replaced during the "boiler exchange campaign" in the Czech Republic was quite low in comparison with the other towns in the county (29% of boilers replaced). The number of houses with solid fuel boilers—511 units; the number of replaced solid fuel boilers—148 units.

Figure 1. Geographical position of the Moravian-Silesian region and selected locations.

2.2. Boiler Types

Overfire boilers—stationary combustion 'hand fired' sources with a natural air supply (no fan ventilation). Fuel is loaded on the grate and the flue gas passes through the layer of fuel. It is the oldest type of boiler.

Gravity feed boilers—incorporating a large hopper above the grate. The fuel descends on to the fire, fed as required, and an inbuilt thermostatically controlled fan assists combustion, providing a quick response to demand.

Pyrolysis boilers—involving a thermal decomposition of materials at elevated temperatures in an inert atmosphere. A highly endothermic reaction is carried out in a special heat-resistant combustion chamber.

Automatic boilers—solid fuel is mechanically fed to a thermostatically controlled combustion. The amount of fuel needed for combustion is automatically managed according to the required boiler performance.

Number of the solid fuel boilers being exchanged in the "boiler exchange campaign" for each of the scenarios is given in Table 1.

Table 1. Number of solid fuel boilers according to location, boiler type and model scenario.

Location	Boiler Type	Scenario A			Scenario B			Scenario C		
		Coal	Wood	Total	Coal	Wood	Total	Coal	Wood	Total
Dolni Lhota	Overfire	6	19	24	1	3	4	0	0	0
	Gravity feed	29	3	33	5	1	6	0	0	0
	Pyrolysis	0	8	8	0	10	10	0	10	10
	Automatic	1	1	2	30	17	47	36	21	57
Kravare	Overfire	21	90	111	3	3	6	0	0	0
	Gravity feed	111	15	126	5	1	6	0	0	0
	Pyrolysis	0	7	7	0	7	7	0	7	7
	Automatic	4	4	8	128	105	233	136	109	245
Vratimov	Overfire	42	142	185	21	101	122	0	0	0
	Gravity feed	225	25	250	150	15	165	0	0	0
	Pyrolysis	0	59	59	0	59	59	0	59	59
	Automatic	9	8	17	105	60	165	276	176	452

2.3. Dispersion Model Scenarios

Three model situations were calculated for each of the locations based on the number of houses with solid fuel boilers, number of replaced boilers, type of solid fuel and type of boiler.

Scenario A represents the air pollution impact of all the solid fuel boilers operated in the chosen location before the start of the "boiler exchange campaign".

Scenario B represents the air pollution impact of all the solid fuel boilers operated in the chosen location after the completion of the Czech subsidized "boiler exchange campaign" in 2018. For this model, it was assumed that mainly the older types of boilers are replaced (batch feed and gravity feed boilers); nevertheless, the type of solid fuel used for heating remains unchanged.

Scenario C represents the air pollution impact of all the solid fuel boilers operated in the chosen location in the theoretical case of complete exchange of all old boilers. For this model it was assumed that all the batch feed and gravity feed boilers are replaced; nevertheless, the type of solid fuel used for heating remains unchanged.

2.4. Calculation of Emissions of Particulate Matter (PM)

The values given in Table 2 were determined as entry data for the calculations of the dispersion model. Specific emissions are expressed as a weighted average of specific pollutants from multiple types of combustion units for a particular type of solid fuel: lignite (lig), bituminous coal (bit) and wood. The specific PM emission values for this study were measured at the Energy Research Centre in Ostrava [21]. The fuel consumption of one household was assessed based on the approximate efficiency of each type of boiler and type of solid fuel used. The set theoretical entry values were as follows: the estimated value of the heating consumption = 100 GJ/year, which is comparable with the value of 124 GJ/year given by Stolarski et al. [22]; an average calorific value of solid fuels commonly used in the area (lignite = 18 MJ/kg; bituminous coal = 25.4 MJ/kg; wood = 14.6 MJ/kg) [23]; and the ratio of the coal use 80 lig:20 bit. The purpose of this study was to model the air pollutant emission load in the selected areas in the worst-case scenario. Thus, the calculations were based on the maximum daily/maximum hourly values of PM during the heating season. The hypothesis for the model is as follows: the heating season lasts approximately 200 days/year, during the hard winter periods it is possible to combust up to 4 times the amount of the average solid fuel quantity. Heating in the Czech Republic accounts for over 50% of the total final energy consumption [24]. Some of the assumptions used in the dispersion model were based on expert evaluations of average values, given that it was not possible to acquire the exact specifications of all the boilers and fuels used for heating. Hence, considering all the given variables, the peak hourly quantity of the PM emission factor was calculated and is given in Table 2; maximum PM emissions were calculated assuming the height of the chimney was 7 m; the chimney diameter was 0.15 m; the flue gas temperature was 70 °C; and the flue gas speed at the end of the chimney was 2 m/s. The representation of dust particles in the individual particle size classes varies according to their origin and chemical composition. The combustion-based particulate emissions from stationary domestic sources are mainly fine particles. The emissions of PM_{10} account for almost 100% of the PM emissions (formerly referred to as total suspended particles—TSP) [25].

Table 2. Particulate emissions per household according to the type of boiler.

Boiler Type	Specific PM Emission			Fuel Consumption		PM Emissions		Max PM Emissions	
	Lig	Bit	Wood	Coal	Wood	Coal	Wood	Coal	Wood
	kg/ton of Burned Fuel			t/Year		kg/Year		g/Hour	
Overfire	24.0	8.9	1.9	10.3	11.4	215.4	21.7	179.5	18.1
Gravity feed	4.9	7.8	1.5	7.7	10.2	42.0	15.3	35.0	12.8
Pyrolysis	-	-	0.6	-	8.6	-	5.1	-	4.3
Automatic	0.8	1.7	0.2	6.4	8.6	6.3	1.7	5.2	1.4

2.5. Emission Dispersion Model

The mathematical modelling system for stationary sources, SYMOS'97 created by the Czech Hydrometeorological Institute in Prague, was used for the additional air pollutant emissions load calculations. The updated version of this model, SYMOS'97 v.2013, was used for this study. This version reflects the legislative changes (Act No. 86/2002 Coll., on air protection). The model is a regional Gaussian dispersion model predicting atmospheric concentrations of pollutants to a distance of up to 100 km from sources and considers the statistical distribution for wind direction and 3 classes of wind velocity (1.7 m/s; 5 m/s; 11 m/s) relative to the stability classes of the airborne particle layer according to the classification of Bubnik and Koldovsky (5 stability classes). Four types of input data are needed in order to perform a model run: terrain elevation; meteorological data; emission data; and receptors/reference points (including spatial information).

The emission dispersion model takes entry emission data and calculates the PM_{10} concentrations for a given reference point (receptor). For the dispersion calculation, the maximum daily PM_{10} values were considered. The reference points were chosen individually for each of the three locations and placed 1m above ground. The reference point details for the given locations are:

- Dolni Lhota—total area 10.44 km^2; 1178 reference points, out of that 531 points in the urban area and 115 reference points in the rural area.
- Kravare—total area 43.92 km^2; 4662 reference points, out of that 263 points in the urban area and 1936 reference points in the rural area.
- Vratimov—total area 26.01 km^2; 2809 reference points, out of that 1414 points in the urban area and 501 reference points in the rural area.

The temperature affects the dispersion of the pollutants. During heating, the temperature can easily reach up to 250 °C, which is beneficial for particle dispersion. Nevertheless, with the high temperature, the chimney heat loss increases and the boiler efficacy decreases, which is contra-productive. Thus, the temperature of the flue gas considered for the air pollution evaluation was established at 70 °C (the initial burning phase for the boilers). This temperature was considered as a daily average flue gas temperature. For each of the reference points (receptors), the spatial information, the maximal daily PM concentrations and the relating wind velocity and direction were chosen for the air pollution dispersion model calculation.

3. Results and Discussion

The air pollution situation at the three monitored locations was assessed with the use of the emission dispersion model software. Each location was evaluated for two zones: the total area of the location and the urban area of the location; the details of the PM_{10} concentrations are given in Table 3. The graphical evaluation of the particulate emission model situation for the location Dolni Lhota is given in Figure 2, for Kravare in Figure 3 and for Vratimov in Figure 4. The numbers connected to individual isolines indicate the maximum daily concentration of PM_{10} in $\mu g/m^3$. The terrain information from each location was used for the dispersion model; graphical terrain presentation can be found in

Figures 1–3, the x-axis and y-axis represent S-JTSK/Krovak GIS coordinates and the z-axis shows the altitude in meters.

Table 3. Minimum, average and maximum daily concentrations of PM_{10} for all three model scenarios and measured average concentrations.

		Modelled PM_{10} (μg/m^3)						Measured PM_{10} (μg/m^3)
		Total Area			Urban Area			
Location	**Scenario**	**A**	**B**	**C**	**A**	**B**	**C**	
Dolni Lhota	Min	3.17	1.40	0.31	6.99	1.97	0.60	44.13
	Avg	18.01	6.92	1.45	40.81	15.72	2.86	
	Max	131.18	103.21	7.83	131.18	103.21	7.83	
Kravare	Min	6.50	1.02	0.61	24.03	6.36	1.87	43.98
	Avg	27.30	7.50	2.36	57.09	21.49	4.50	
	Max	123.32	84.49	8.02	123.32	84.49	8.02	
Vratimov	Min	7.84	4.95	0.82	14.80	10.86	1.49	34.38
	Avg	37.70	27.30	3.14	50.72	38.24	3.90	
	Max	192.12	192.12	12.29	192.12	192.12	9.42	

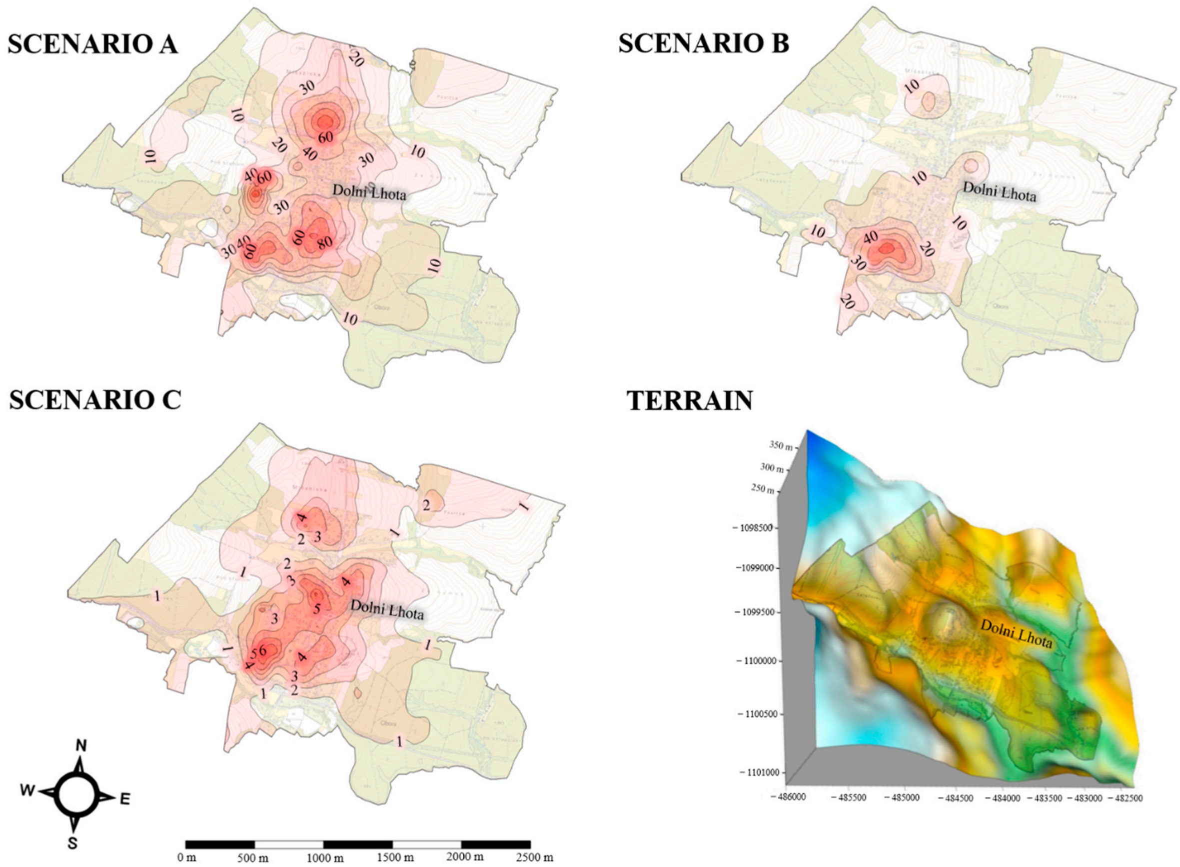

Figure 2. Particulate emissions dispersion model for the location Dolni Lhota.

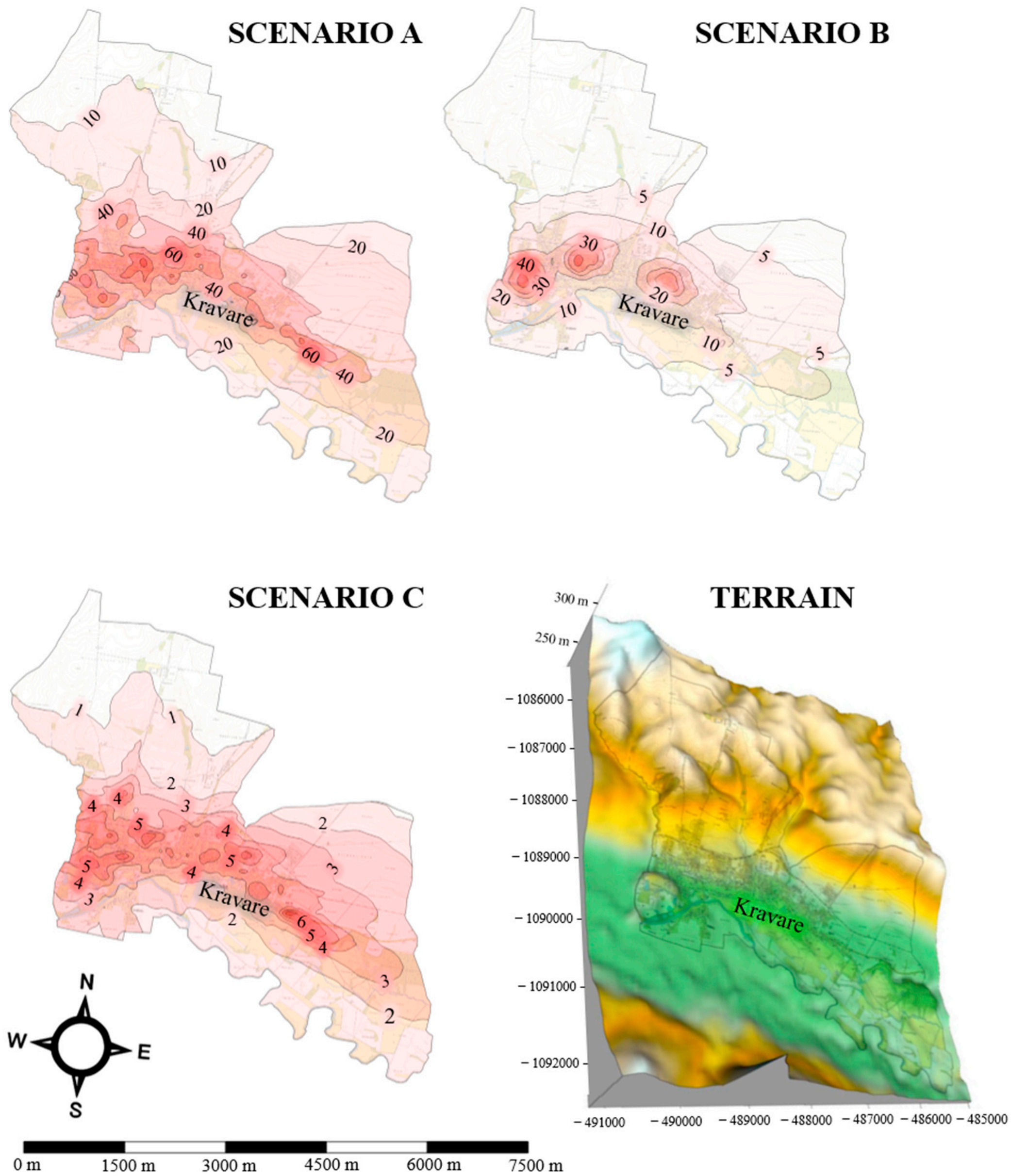

Figure 3. Particulate emissions dispersion model for the location Kravare.

3.1. Dolni Lhota

For the Dolni Lhota total area and urban area, the maximum concentrations of PM_{10} remain the same. In the case of scenario B, after a partial exchange of the solid fuel boilers (46 out of 67 devices), the average daily airborne particle pollution dropped by almost 62%. In the case of scenario C with the hypothetical full exchange of boilers, the average daily airborne particle pollution decreased by 92%. Air pollution in Dolni Lhota is greatly affected by the hilly terrain, which encloses the village. The highest PM_{10} concentrations were observed at the foot of the ascending land (e.g., the house with the boiler is positioned in the valley). An Italian study has also mentioned a particulate emissions issue in Aosta Valley due to the confinement effect of mountains [26].

3.2. Kravare

For the Kravare total area and urban area, the maximum concentrations of PM_{10} remain the same. In the case of scenario B, after a partial exchange of the solid fuel boilers (225 out of 252 devices), the average daily airborne particle pollution dropped by almost 73%. In the case of scenario C with the hypothetical total exchange of boilers, the average daily airborne particle pollution decreased by 91.4%. The urban area average air pollution concentration decrease is slightly lower (by 10%) than in the total area of the town. The highest PM_{10} concentrations were observed in the most populated urban area of the town. The flat terrain surrounding the town does not impact air pollution. Nevertheless, the maximum daily concentrations during scenario B remain locally very high (up to 84.5 μg/m^3) during the heating season. Only after the total boiler replacement, as modelled in scenario C, the maximum PM_{10} concentrations rapidly decrease to 8 μg/m^3.

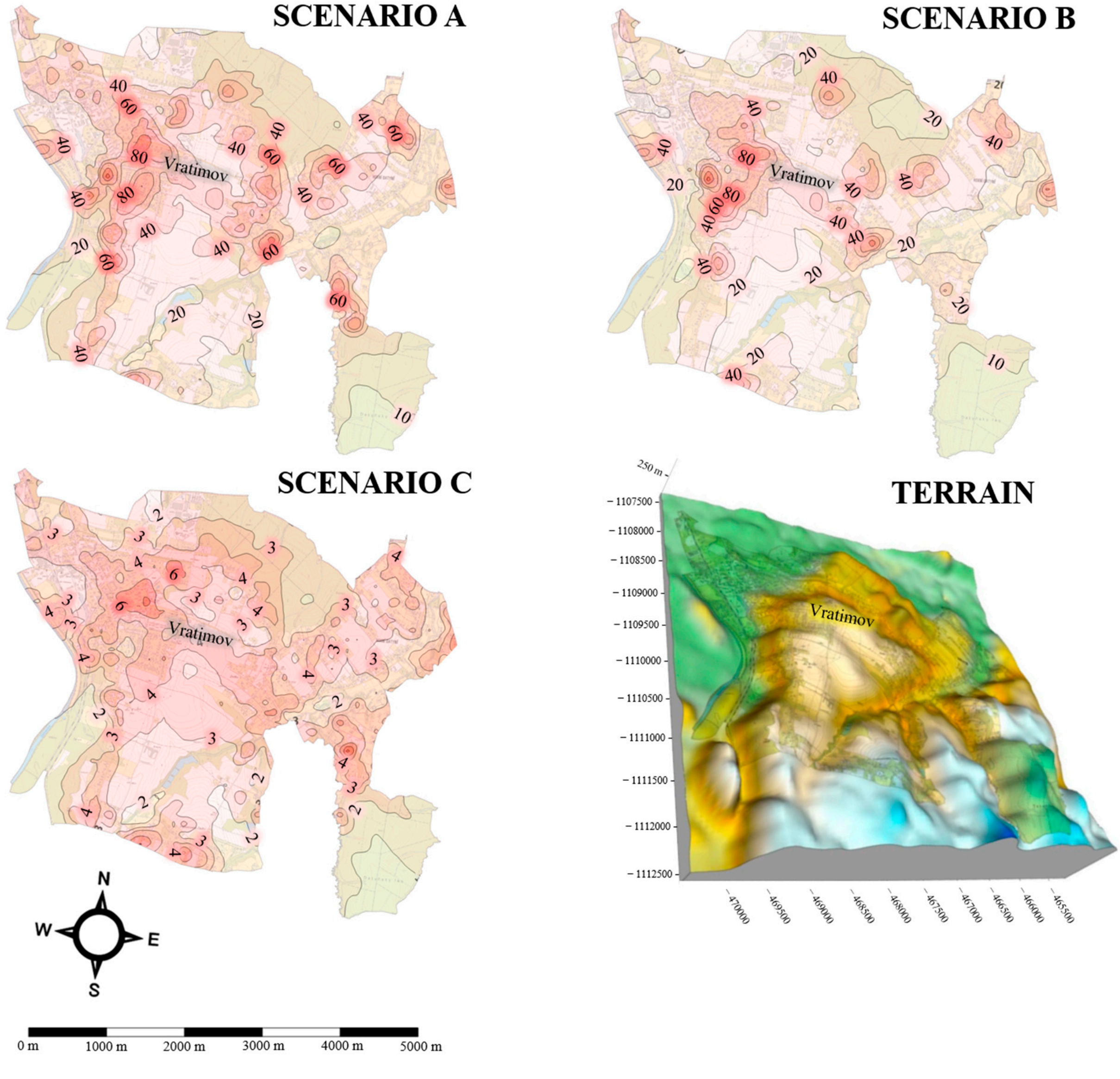

Figure 4. Particulate emissions dispersion model for the location Vratimov.

3.3. *Vratimov*

The maximum daily PM_{10} concentrations remain the same in the total area and urban area of the town. Interestingly, even after the partial exchange of the solid fuel boilers, scenario B (148 out of 511 devices), the maximum daily concentrations remain unchanged. The average daily airborne particle pollution during scenario B dropped by 27.6%. In the case of scenario C with the hypothetical total exchange of boilers, the average daily airborne particle pollution decreased by 91.7%. The highest PM_{10} concentrations were observed in the most populated urban areas of the town, with the highest amount of solid fuel boilers. The most populated areas are located on the hilly terrain, which might influence the air pollution concentrations. Furthermore, after a partial boiler exchange (scenario B), only 29% of boilers were replaced; thus, the maximum daily concentrations remain locally very high (up to 192 µg/m^3) during the heating season. Only after the total boiler replacement, as modelled in scenario C, the maximum PM_{10} concentrations rapidly decrease to approximately 12 µg/m^3.

All three locations are located in an outstandingly polluted area of the Moravian-Silesian region. This is a traditional coal-mining region with heavy industry and a relatively high level of urbanization. The average yearly concentrations of PM_{10} in the ambient air in this region have not been significantly decreasing in the past years but remain quite high in the range of 30.9 µg/m^3 in 2016 to 33.8 µg/m^3 in 2018 [27]. For the comparison of the modelled data of PM_{10} concentrations, we conducted a series of PM_{10} measurements in Dolni Lhota and Vratimov, using a hi-vol air sampler, during the heating season in 2018 (Figure 5). For the same days, we obtained data from the Czech Hydrometeorological Institute from the Opava-Katerinky station (located approximately 7 km from Kravare). Furthermore, a series of PM_{10} measurements were conducted during the smog situation in February 2018 in Dolni Lhota. Nonetheless, even after a partial solid fuel boiler exchange in selected locations, the average daily concentrations of PM_{10} still remained high during the heating season. The highest measured average daily concentration of PM_{10} was determined for the Kravare site (82.5 µg/m^3). Higher PM_{10} concentrations were observed during the smog situation in Dolni Lhota, approximately 25% higher than average concentrations throughout non-smog winter days.

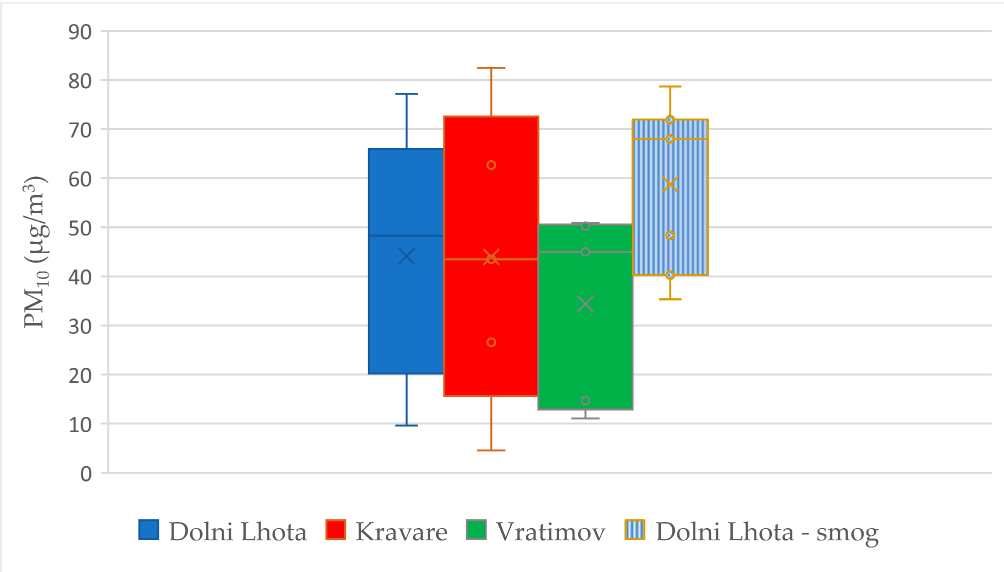

Figure 5. Boxplot-type comparison of daily average PM_{10} concentrations on selected days during the heating season in 2018.

Typical for the northeast part of the Czech Republic is a predominant airflow from the southwest (mainly during a cyclonic, low-pressure-type of weather) coming from other parts of the Czech Republic, Germany and Austria. Conversely, there is an opposite northeast airflow coming transboundary from Poland with low wind velocities, associated with anticyclonic situations (high-pressure systems), which is often accompanied by worsened dispersion conditions, especially during the cold period of the year. According to a transboundary (Polish–Czech border) air-pollution report, there was both a much higher pollution load and a much higher frequency of days with average PM_{10} concentrations above 50 µg·m^{-3} (daily limit value) and 100 µg·m^{-3} during days with airflow direction from Poland to the Czech Republic [28]. According to another extensive study of air pollution in this area [27], the main cause of PM pollution is individual residential heating. The findings of this study also suggest that the main air pollution contributor is residential heating, since Kravare and Dolni Lhota are locations with no industry in contrast to Vratimov, yet the PM_{10} concentrations there are significantly higher during the heating season. This is in agreement with Godec et al. [29] who measured concentrations of PM_{10} in Zagreb, Croatia in summer (19.4 $\mu g \cdot m^{-3}$) and winter (43.6 $\mu g \cdot m^{-3}$); Schwarz et al. [30] who measured concentrations of PM_{10} in Prague, Czech Republic in summer (20 $\mu g \cdot m^{-3}$) and winter (38.1 $\mu g \cdot m^{-3}$); and Błaszczak et al. [31] who measured concentrations of $PM_{2.5}$ in Raciborz, Poland in summer (14.76 $\mu g \cdot m^{-3}$) and winter (55.36 $\mu g \cdot m^{-3}$). Actual measurements of PM_{10} performed at selected locations during the heating season in 2018 (equivalent to scenario B) suggest that the average levels of air pollution remain very high (Table 3). There is a substantial difference between the measured and modelled daily average PM_{10} concentrations for the two nonindustrial sites; the measured values were significantly higher for Dolni Lhota by 64% and for Kravare by 51%. Hence, it can be assumed that PM long-range or/and transboundary transports were involved. The highest average PM_{10} concentrations were measured during the same day (22 January 2018) at all three locations (Dolni Lhota 77.19 $\mu g \cdot m^{-3}$; Kravare 82.5 $\mu g \cdot m^{-3}$; Vratimov 50.9 $\mu g \cdot m^{-3}$). According to the air pollutant dispersion model study issued by the Public Health Institute Ostrava [32], the transboundary transport trajectories were calculated using the HYSPLIT model for the same day, with results shown in Figure 6. The results of the HYSPLIT modelling were used for evaluation of a possible transboundary transport of air pollution and for targeting a possible industrial source. The model was only calculated for one selected day, and further work is needed to examine the long-range pollution impact on selected locations.

Sources: Esri, HERE, DeLomme, USGS, Intermap, INCREMENT P, NRCan, Esri Japan, MEZI, Esri China (Hong Kong), Esri Korea, Esri (Thailand), MapmyIndia, NGCC, © OpenStreetMap contributors, and the GIS User Community

Figure 6. A 24 h air pollutant dispersion trajectory for Ostrava, calculated for 22 January 2018.

The transboundary transport trend was not observed at the industrial location Vratimov, where the difference between the modelled and measured daily average PM_{10} concentrations was approximately 10%, suggesting that residential heating and the local metallurgical industry were the main contributors to the air pollution.

4. Conclusions

The results of this study show three model situations of PM10 emissions dispersion linked with solid fuel boiler replacement. The model covers past (A), present (B) and future (C) scenarios of three selected urban locations in the Czech Republic regarding the pollution situation caused by local heating, with emphasis on fine dust particles. It can be concluded that for all three locations, the highest values of PM10 concentrations were observed in the most populated urban areas with the highest number of solid fuel boilers in use for heating together with the areas located at the foothills.

As a matter of fact, partial boiler exchange (scenario B) does improve the PM emission situation in urban areas. Nevertheless, older types of solid fuel boilers emit considerably more dust emissions in comparison with modern devices. Thus, a significant improvement in outdoor air quality can be expected after the vast majority of the old-style solid fuel boilers (overfire and gravity feed) are replaced by automatic ones or alternative types of heating (solar, heat pumps). The results of model scenario C suggest that after the complete exchange of the older types of boilers, there will be a significant decrease in dust pollution levels (up to 92%), even without the change of solid fuel type.

There is an urgent need to develop and promote the use of the best available combustion technologies producing low emissions since residential solid fuel combustion for heating will continue to be used in many parts of the world. Especially coal, wood and other types of biomass, which will remain as major sources of fuel in the near future because of the economic considerations and availability of other types of fuels. Strong policy actions to upgrade existing boilers and reduce the impact on air quality are also mentioned by Casasso et al. [26].

The purpose of this study was to evaluate whether residential heating impacts air quality. It is clear that there is a direct correlation between the number of solid fuel boilers and PM concentrations. The findings of this study suggest that the main air pollution contributor is residential heating since Dolni Lhota (daily average of PM_{10} = 44.13 $\mu g \cdot m^{-3}$) and Kravare (daily average of PM_{10} = 43.98 $\mu g \cdot m^{-3}$) are locations with no industry in contrast to heavily industrial Vratimov (daily average of PM_{10} = 34.38 $\mu g \cdot m^{-3}$), which were measured during the heating season. From the difference in PM concentration levels in scenario B (partial boiler exchange) and scenario C (full boiler exchange), it can be assumed that there will be a significant decrease in PM concentrations after the vast majority of old-style solid fuel boilers are replaced by automatic solid fuel boilers or alternative sources of energy (solar, heat pumps). Actual measurements of PM_{10} performed at selected locations during the heating season in 2018 (comparable to scenario B) suggest that the average levels of air pollution remain very high. For the two nonindustrial sites, the measured values were significantly higher than the modelled values for Dolni Lhota by 64% and for Kravare by 51%. Thus, it was assumed that PM long-range or/and transboundary transports were involved.

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