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Analysis of emission abatement scenario to improve urban air quality

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Abstract: Air quality in Warsaw is mainly affected by two classes of internal polluting sources: transportation and municipal sector emissions, apart from external pollution inflow. Warsaw authorities prepared strategies of mitigating emissions coming from both these sectors. In this study we analyze effects of the implementation of these strategies by modeling air pollution in Warsaw using several mitigation scenarios. The applied model, operating on a homogeneous discretization grid, forecasts the annual average concentrations of individual pollutants and the related population health risk. The results reveal that the measures planned by the authorities will cause almost 50% reduction of the residents' exposure to NOx pollution and almost 23% reduction of the exposure to CO pollution due to the transport emissions, while the residents' exposure reductions due to the municipal sector are 10% for PM10, 15% for PM2.5, and 26% for BaP. The relatively smaller reductions due to municipal sector are connected with high transboundary inflow of pollutants (38% for PM10, 45% for PM2.5, 36% for BaP, and 45% for CO). The implementation of the discussed strategies will reduce the annual mean concentrations of NOx and PM2.5 below the limits of the Ambient Air Quality Directive. Despite the lower exposure reduction, the abatement of municipal sector emissions results in a very significant reduction in health risks, in particular, in the attributable mortality and the DALY index. This is due to the dominant share of municipal pollution (PM2.5 in particular) in the related health effects.

Introduction

According to the World Health Organization (WHO, 2018), air pollution remains the main environmental health risk in Europe, especially in urban agglomerations. Urban inhabitants' exposure to air pollutants is the most important cause of the population health risk, due to a high concentration of human activities (like industrial, municipal, transport, etc.) responsible for pollutants emissions. Numerous European cities regularly exceed the air quality standards prescribed by the Ambient Air Quality Directive (EC 2008, EEA 2019, WHO 2018), which makes this problem to be of high atmospheric environmental concern.

In the source apportionment analysis (EC 2015, WHO 2015) the transportation system is usually pointed out as an emission category having the dominating share in the air quality degradation in most towns. Also, the proposed emission abatement scenarios (EC 2016, EC 2019) are mainly related to traffic measures. Many earlier urban scale studies addressed emissions of the road transport pollutants. Berkowicz et al. (2003) consider the traffic related NOx and CO pollution in Copenhagen, with differentiation between vehicle types, fuel used, engine capacity and emission legislation class. The same pollutants are discussed by Buchholz et al. (2013) for Luxembourg, aiming at reducing their annual mean concentrations. In the emission scenarios for the years 1998–2006, they consider the dominating sources, i.e. the road transport and nonindustrial combustion. An integrated analysis of NO_2 and CO concentrations in Turin is presented by Calori et al. (2006). Mediavilla-Shagún and ApSimon (2006) consider integrated analysis of PM_{10} pollution in London. Oxley et al. (2009) discuss the impact of NO_2, NOx, and PM_{10} that are considered as the main traffic-related pollutants in London. Integrated modeling is used to link emissions, pollution concentrations, human exposure and possible emission abatement techniques as well as policy implications (Rith at al. 2020). However, the situation in Eastern European cities is different than in Western European ones. The transportation fleet in the former ones is much older, and thus the emissions are distinctly higher, hence the range of possible reduction is greater. Warsaw is quite a specific city, not only taking into account the Eastern European but even the Polish conditions. It concerns not only spatial distribution of emissions but also the fact that Warsaw practically lacks densely-built canyon-like streets which are quite frequent in other large cities.

In numerous recent studies, (e.g., Costa et al. 2014, Degraeuwe et al. 2017, Holnicki at al. 2017a–b, Bebkiewicz et al. 2020, Kariagulian et al. 2015, Tainio 2015, WHO 2015, WHO 2018) and in many others, nitrogen oxides, NO_2

(the highly reactive fraction of NOx) as well as primary and secondary $PM_{2.5}$ (the fine fraction of PM_{10}) are blamed to cause the greatest harmful health effects. At the same time, in many cities the annual average concentration limits, both for NO_2 (40 mg/m^3) and $PM_{2.5}$ (25 mg/m^3) (Juda-Rezler et al. 2020, EC 2008,2015) are frequently exceeded. The dominating source of NO_2 pollution in urban agglomerations is the road transport, mainly due to emission from diesel cars (Degraeuwe et al. 2019, EC 2016, EC 2019). Traffic is also an important source of the re-suspended, coarse fractions of particulate matter. Hence, recently published European studies assessed the effects of traffic policies, intended to reduce concentrations of the above species in large cities. In particular, Degraeuwe et al. (2017) showed that the reduction of NOx emission by diesel cars after conversion from the current to Euro 6 level can significantly decrease regional and urban NO_2 concentrations (results for 8 selected urban agglomerations). Moreover, various NOx emission abatement scenarios considering implementation of Euro 6 diesel car emission norm in urban traffic, are analyzed in *Urban NO_2 Atlas* (Degraeuve et al. 2019) for 30 major European cities. The reduction studies use the SHERPA--City methodology (EC 2019, Pisoni et al. 2019, Thunis et al. 2016). Karagulian et al. (2015) analyze sources affecting PM_{10} and $PM_{2.5}$ pollution in main regions of Europe using the source apportionment method (see also a review by Thunis et al. 2019) and considering traffic, industrial activity, domestic fuel burning, unspecified pollution, and natural sources. This approach, conducted in cities in 51 countries, was used in this study to calculate regional averages of ambient particulate matter sources.

Warsaw, similarly as many other European agglomerations, also suffers from high concentrations of air pollutants characterizing the urban atmospheric environment, like particulate matter, sulfur- and nitrogen oxides, carbon monoxide, some heavy metals, as well as sometimes polycyclic aromatic hydrocarbons. In Warsaw, the specific structure of the local emission field is mainly connected with the following two emission categories:

(i) The first of the dominating pollution category is the traffic-induced emission. The number of cars registered in Warsaw steadily increases, particularly in the last decade (SMOGLAB, 2016), contrary to many other European cities. The traffic originated emissions are mainly responsible for NO_x, CO, and C_6H_6 concentrations, but also contribute to PM_{10} pollutions, mainly via the re-suspended coarse fraction (Kiesewetter et al. 2014, Holnicki et al. 2016, Połednik et al. 2018). In particular, high NO_x and PM_{10} concentrations persisted during the last decade (Costa et al. 2014, Holnicki et al. 2017a, EC 2019).

(ii) The second and, in a sense, even more important emission category relates to coal combustion which is the main fossil fuel used by the Polish industry and power stations, but also for the individual household heating. Although the district heating system operates in the central part of Warsaw, in the peripheral districts as well as in the neighboring satellite towns and rural areas the coal fired installations are used, which considerably contribute to deterioration of the urban air quality. These emission sources are responsible for particulate matter pollution (especially $PM_{2.5}$), SO_2, some heavy metals and highly toxic B(a)P (EEA 2018, EEA 2019). The last pollutant, emitted by the municipal sector, constitutes a serious general problem in whole Poland, and its inflow from distant sources contributes considerably to the overall concentration in Warsaw (Holnicki et al. 2017a–b, 2018).

This study investigates what may be an effect of reducing pollution emission by traffic and coal fueled household installations on air quality in Warsaw. Projects planned by the Warsaw authorities are considered, both regarding traffic and household heating. To fully assess environmental benefits coming from the implementation of these projects, the reference year 2012 has been chosen, prior to the projects initializations.

Methods

Model simulation

Modeling of atmospheric pollution dispersion in the city was carried out using the Gaussian regional model CALPUFF, v.5 (Scire et al. 2000) with the CALMET meteorological preprocessor. A limitation of CALPUFF is in modeling chemical transformations. However, it is of low importance in urban scale modeling due to short time when pollutants emitted by local sources remain in the studied domain. This limitation would be more substantial for the contributions coming from the outside sources. But the secondary pollutants (aerosols) resulting from chemical transformations in such contributions are included in our modeling via the boundary conditions. Spatial maps of the average annual concentrations of major air pollutants were obtained in order to determine areas where the permissible concentration levels of individual pollutants were exceeded and to identify the sources of emissions responsible for the exceedances.

The emission field combines a large number of sources that differ in technological parameters, emission characteristics, composition of emitted compounds, and assigned uncertainty (Holnicki et al. 2016, 2017b). It was divided into several categories according to their emission characteristics (the number of sources in a given category is shown in brackets): (a) high energy point sources (24), (b) other industrial point sources (3880), (c) linear sources of the transport networks (7285), (d) surface sources of the municipal sector (6962). The external (transboundary) inflow of pollutants entering via boundary conditions of the forecasting model, is also taken into account. The baseline emission data used for calculation of the initial concentration distribution were the official data provided by the Mazovian Inspectorate of Environmental Protection.

For the calculation of pollutants concentrations, the Warsaw metropolitan area (about 520 km^2 within administrative boundaries) was digitized with a homogeneous grid 0.5 km × 0.5 km. Using emission data given in this grid, the resulting concentrations were calculated in 2248 elementary mesh receptors. The calculations were performed for emission and meteorological data in 2012. The following most important pollutants characterizing the urban atmosphere were analyzed: PM_{10} and $PM_{2.5}$ dust, NOx, SO_2, Pb, CO, C_6H_6, B(a)P, and heavy metals. The average annual concentration values of individual pollutants, averaged over the area of an elemental receptor, were adopted as final value for this receptor.

Computer simulations provide annual mean concentration maps showing distributions of the main pollutants that characterize the urban atmospheric environment. They also indicate which pollutants exceed the limit values and where these violations are the highest. The linear structure of the CALPUFF model allows for indication of the emission categories responsible for standards violation (source apportionment). Moreover, it is possible to quantify the percentage share of an individual emission source category in the total concentration at a given receptor point or in a district. This is very useful for elaborating an abatement strategy to improve the city air quality.

The maps in Fig. 1 show the spatial distribution of the pollutants that had the greatest impact on the air quality deterioration in the city. They refer to emission data in 2012, which form the baseline dataset in the analysis of emission scenarios aimed at a definite improvement of the city air quality. The limit concentrations are exceeded for both NO_x and B(a)P (top panel) as well as by particulate matter, PM_{10} and $PM_{2.5}$ (bottom panel). The nitrogen oxides and PM_{10} pollution is mainly caused by the road transport, while the benzo(a)pyrene and $PM_{2.5}$ particulate matter come primarily from combusting the coal in the city municipal sector, with a significant share from the transboundary inflow. The limit level of the annual mean B(a)P concentration (1 ng/m^3) is exceeded in the whole city, which reflects a general situation related to the strong domination of coal in the fuel mix in Poland (EEC 2018, 2019; Holnicki et al. 2017a). These pollutants whose average annual concentrations do not exceed the permissible levels, e.g. SO_2, CO, C_6H_6 (Holnicki et al. 2017a), are omitted but they also contribute to air quality deterioration in the city, especially when considering their synergistic interaction with other compounds.

Emission abatement scenarios

In the sequel, several scenarios for reducing emissions of the main contributors: the road transport (line sources) and the municipal sector (area sources) are discussed. The implementation of Euro 6 emission norms for passenger cars is considered as well as the modernization of the municipal housing heating systems. The former analysis is based on the results presented in the *Urban* NO_2 *Atlas* (Degraeuwe et al. 2019) where, using the national emission data, the NO_x emission rates per fuel and Euro norm for 30 cities are collected. Among them, the Warsaw transportation system structure and emission properties are fully specified by the fleet composition, fuel type used, yearly distance driven, and emission rates connected with the Euro norms depending on cars production years. These data are used to assess the emission reduction rate connected with the emission policy scenarios for the transportation system, in particular these of achieving the Euro 6 emission norm by cars.

The policy of the Warsaw environmental protection authorities, mainly regarding public transport and the municipal sector, was taken into account. The implementation of the hybrid/LNG/CNG technology in the public transportation system is considered in the former case and the subsidized modernization of the heating installations in the municipal

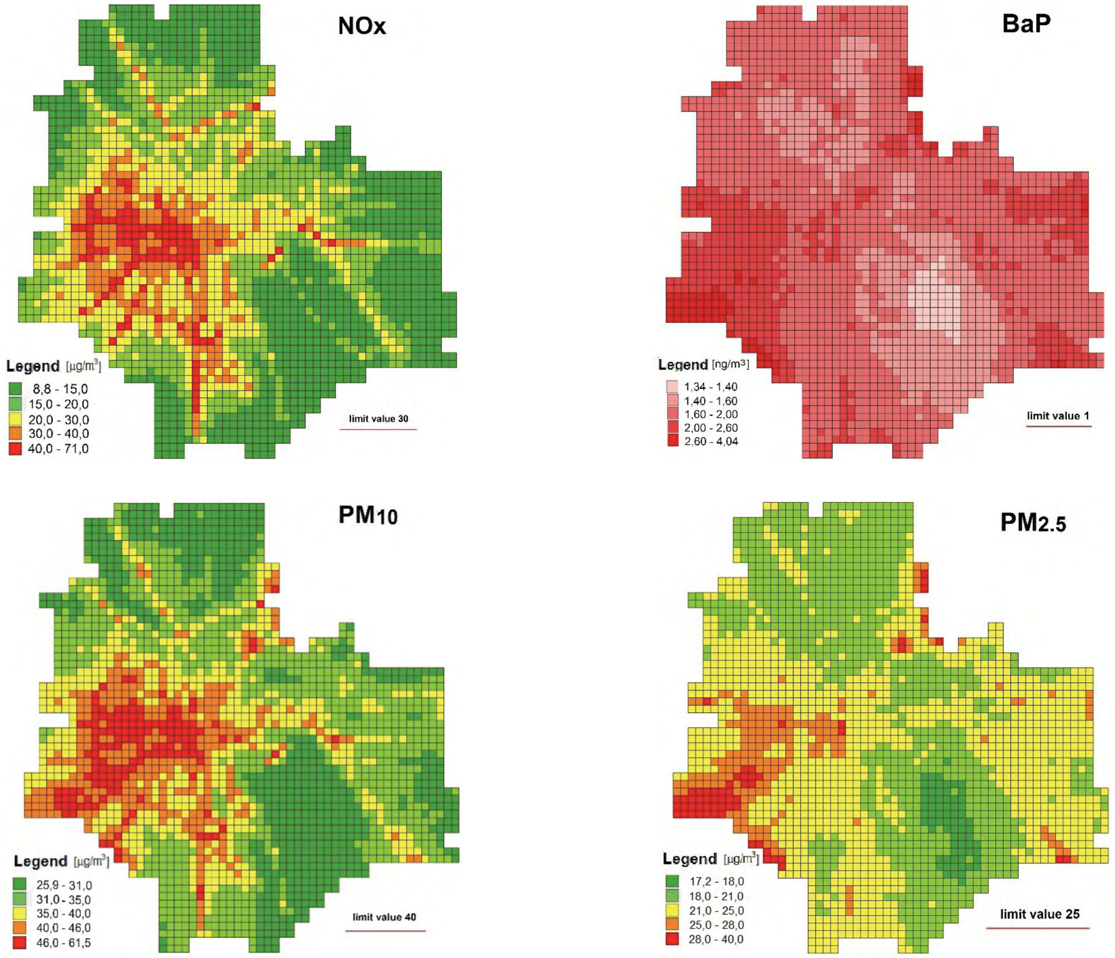

Fig. 1. The annual mean concentrations: NO_x and BaP (top); PM_{10} and $PM_{2.5}$ (bottom) in 2012

sector is taken into account in the latter. The related environmental effects, including the reduction of residents' exposure to a given type of air pollution, are presented as the concentration maps that can be compared with the baseline values shown in Fig. 1.

The analysis does not take into account all factors that influence pollutant emissions in the city. Among them is the growth of population that involves increase of private cars in the city, as well as additional authority activities, besides those discussed above, like promotions of the public transport (expansion of the metro, tram and railway lines, introduction of the bus passes on the most crowded roads) or development of new ring roads. These factors do affect the pollutants emissions, both in quantity and spatial distribution, but in a lesser scale (see also discussion in Holnicki at al. (2018)).

Results – emission abatement scenarios

The nitrogen oxides pollution

The car traffic is usually a dominating source responsible for NO$_x$ pollution in urban areas. As shown in Fig. 2, transportation contributes 77% to the overall NO$_x$ concentration in Warsaw, while among emission categories 10% comes from the area sources and 8% from the transboundary inflow.

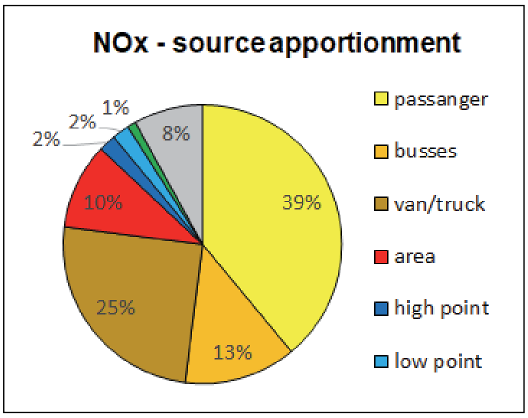

Fig. 2. Source apportionment for NO$_x$ emissions

The first scenario considered consists in reducing the nitrogen oxides concentration by achieving ultimately the Euro 6 emission norm by the passenger cars (39% emission share) as well as the application of the low-emission technologies in the urban transport buses (13% emission share).

There is a significant difference in NO$_x$ emissions rate between diesel and gasoline cars, with a definite prevalence of the former ones. This discrepancy is taken into account in the emission scenarios discussed below. Similarly, as in other Eastern European cities, in terms of the fuel consumption there is a significant dominance of low emission norms (E0–E3) in Warsaw, both for the gasoline and diesel cars (Degraeuwe et al. 2019). The data placed there are used to calculate the annual emission volume assigned to car categories and Euro norms. Table 1 presents the annual NO$_x$ emissions in Warsaw, attributed to each Euro norm (compare Tables S1–S3; Dieselnet_LD 2019, Dieselnet_HD 2019, Transportpolicy 2018) that are calculated as a product of yearly kilometers driven and the respective emission rate (cf. Fig. S1; Degraeuwe et al. 2019).

In our study we assume Euro 3 emission rate for all pre-E4 cars, both diesel and gasoline (it is the first among the NO$_x$ standards in Tables S1–S2), as it can be assumed that the E3 cars prevail among the older ones. This is supported by the data presented in Bebkiewicz at al. (2020) where distances travelled in whole Poland by E3 cars visibly prevail starting from 2010. Moreover, it can be expected that cars in Warsaw are replaced on average more frequently with new ones because the financial income of Warsaw inhabitants is relatively higher than the Polish average. The Euro 6 norm is adopted as the target to be obtained by both car categories. The share of the total NO$_x$ emission from the older (pre-E4) car categories is 19% for the gasoline and 59% for diesel cars (Table 1). It follows from the Euro norms (Tables S1–S2) that the emission reduction rate, referring to the transition from E3 to E6, is 0.4 for the gasoline cars and 0.16 for the diesel cars, which enable determining the target NO$_x$ emissions from conversion from the pre-E4 to E6 norm. Emission rates for the E4–E6 vehicles are left unchanged. The results in Table 2 show that meeting the Euro 6 standard by passenger cars in Warsaw would reduce NO$_x$ emissions by about 60%, as compared to the baseline level.

Table 1. Baseline NO$_x$ emissions per fuel and Euro norm

	Euro norm	Distance [km*10^6]	Emis. rate [g/km]	Emission [Mg]	Share [%]	Share
GASOLINE	E0	789	2,5	1974	2%	17000 (19%)
	E1	15789	0,45	7105	8%	
	E2	24737	0,25	6184	7%	
	E3	11579	0,15	1737	2%	
	E4–E6	13684	0,1	1368	2%	1368
	emission			**18368**	**21%**	18368
DIESEL	E0	6316	0,66	4168	5%	52742 (59%)
	E1	25789	0,73	18826	22%	
	E2	24211	0,8	19368	22%	
	E3	11579	0,83	9611	11%	
	E4–E6	26316	0,65	17105	20%	17105
	emission			**69079**	**79%**	69847
TOTAL				**87447**	**100%**	

A change of the concentration distribution due to meeting the Euro 6 standard is visible in Fig. 3b.

As can be seen from Fig. 2, public transport buses have a significant share in the total NO_x concentration (about 13%). The city authorities have launched a replacement of the bus fleet with low-emission vehicles, and ultimately public transport will be served only by this type buses (hybrid, LNG/CNG). The reduction of the NO_x emission in the public transport fleet is estimated (expert opinion) at 40–60%. This adds to atmosphere NO_x concentration reduction. The additional reduction due to low-emission busses on NO_x concentration distribution is visible in Fig. 3c. Similarly, the transition to low emission Euro norms by heavy duty vehicles (Table S3) also significantly contribute to the overall concentration. The additional change caused by this transformation is presented in Fig. 3d.

Summarizing, the intermediate and final distributions of NOx concentration in the city, corresponding to the adopted car fleet emission scenario, are presented in Fig. 3. The attached concentration maps show the effect of implementing successive parts of the discussed scenario for the subsequent

Table 2. Reduction of the NO_x emissions for the target Euro 6 norms.

	Euro norm	Baseline emission [Mg]	Final emission [Mg]	Reduction [%]
GASOLINE	E0–E3	17000	6800	
	E4–E6	1368	1368	
	∑ gasoline	**18368**	**8126**	**56%**
DIESEL	E0–E3	51194	8316	
	E4–E6	17105	17105	
	∑ diesel	**69079**	**27653**	**60%**
	TOTAL	**87447**	**35779**	**59,1%**

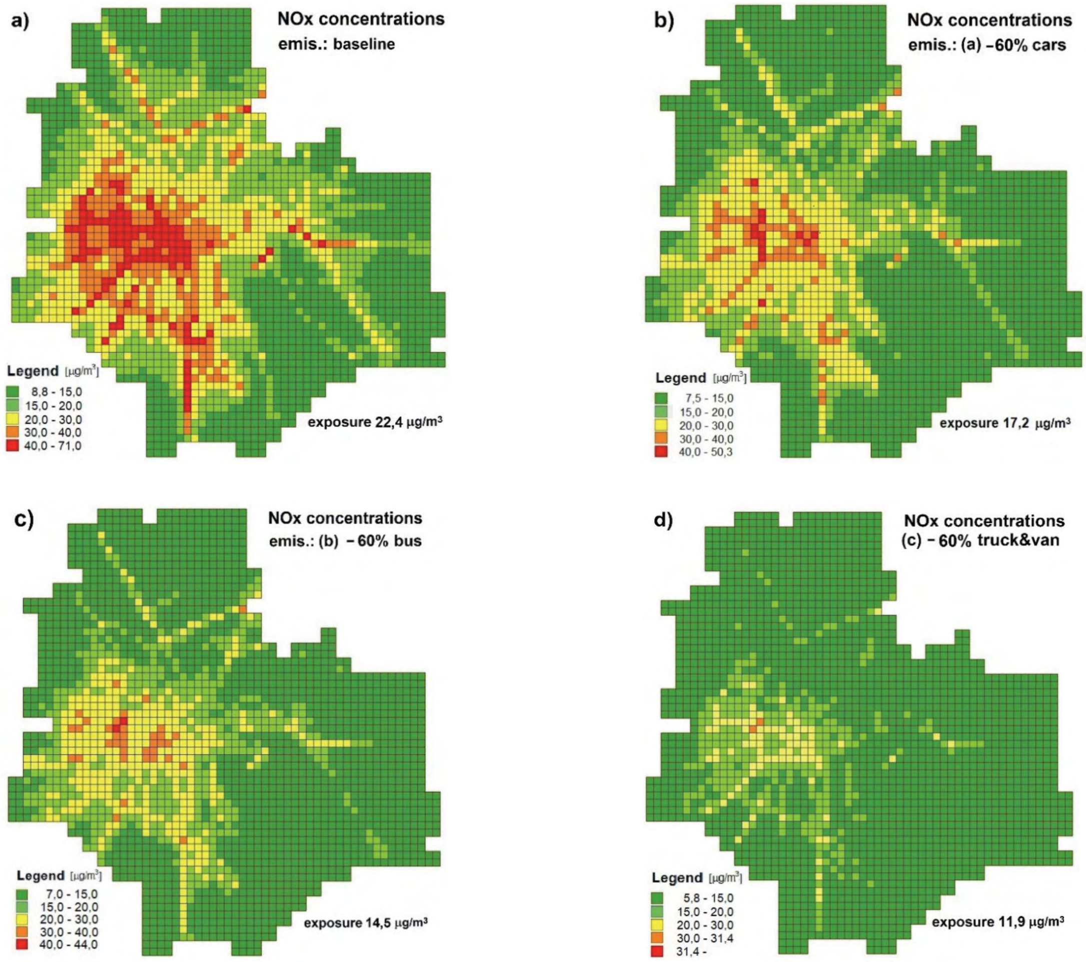

Fig. 3. NO_x concentrations: (a) baseline emission, (b) Euro 6 norm by passenger cars (emission – 60%), (c) + bus emission reduction (-60%), (d) + Euro 5 norm met by trucks & vans (emission – 60%). Change of inhabitants exposure is given in the lower right corners

categories of motor vehicles. The comparison of Fig. 3a and Fig. 3d maps shows that the full implementation of the scenario decreases the residents' exposure to NO_x pollution by almost 50%, while at the same time the concentration limit value is slightly exceeded in only two receptors.

The carbon monoxide

Although CO concentrations do not exceed the accepted limit value (EC 2008), this pollution also strongly depends on car traffic, as shown in Fig. 4. Therefore, tightening emission standards will also help to limit this very harmful pollution in the urban area.

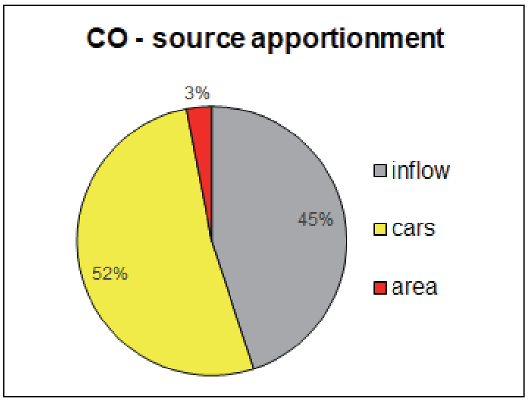

Fig. 4. Source apportionment for CO emissions

In this case, however, the car emission profile fundamentally differs from that for NO_x, and the gasoline cars have a decidedly dominant share in CO emissions. This fact is also reflected in the Euro norms for CO emissions, as can be seen in Tables S1–S2. The situation is particularly evident in the Eastern European cities (e.g., in Warsaw), where pre-E4 cars dominate in the vehicle fleet (Degraeuwe et al. 2019, EC 2019). The adoption of Euro 6 as the target emission norm implies a reduction of the baseline CO emissions by about 57% (compare Table S1) for all the pre-E4 gasoline cars. Maps in Fig. 5 compare the reference distributions of the annual mean CO concentration and that which relates to Euro 6 norm applied to the passenger cars. The maps show a significant reduction of CO pollution, especially in the central districts.

The particulate matter

As seen in Fig. 6, the road traffic significantly contributes to particulate matter pollution of an urban area, especially in the case of PM_{10} concentration. However, the implementation of Euro 6 emission standard will not bring a significant improvement in air quality in this case, for at least two reasons. First of all, PM_{10} pollution emitted by cars consists of two components: dust emitted directly by cars (primary emission) and re-suspended one (secondary emission). The second component comes from all types of sources, including the external inflow.

Measurements carried out in Warsaw (Table S4; WIOŚ 2013) revealed that the secondary emissions of PM_{10} account

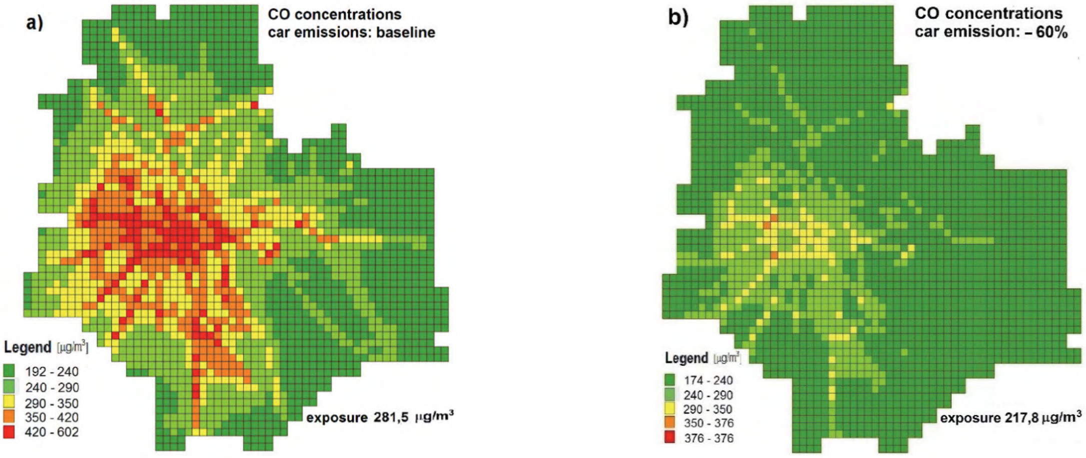

Fig. 5. The baseline CO concentration (a), and after implementation of Euro 6 norm for passenger cars (b)

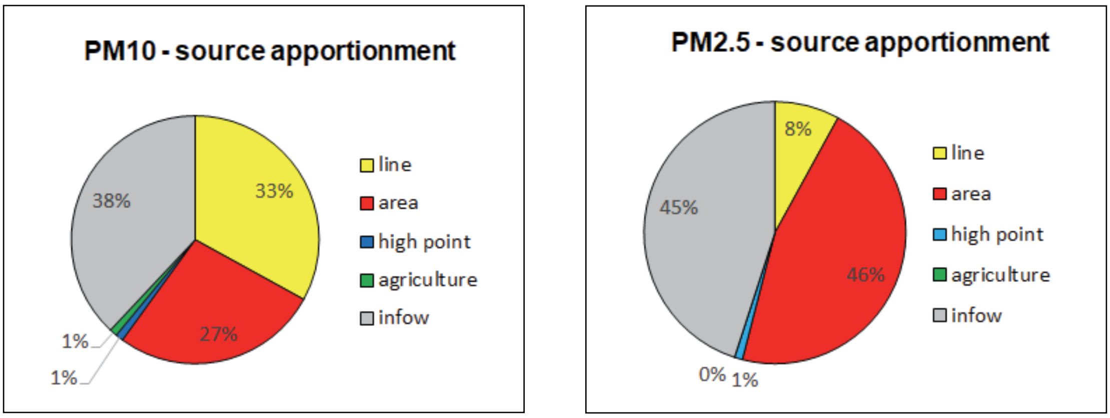

Fig. 6. Source apportionment for PM_{10} and $PM_{2.5}$ emissions

for around 80% of the total volume. Moreover, the remaining 20% (primary emission) also consists of two components: emissions from the fuel combustion and from the friction (abrasion of tires, brake linings, etc.). As a result, the fuel combustion has only about 12% share in PM_{10} total emission (Table S4). Hence, ultimately, the implementation the Euro 6 emission norm in passenger cars and busses can reduce the concentration of PM_{10} in the city only by about 2–3%, with a minor improvement seen in the central districts only.

Contribution of the primary and re-suspended emissions to the final $PM_{2.5}$ concentration is more balanced (compare Table S4), also the share of the fuel combustion is more considerable, but due to the relatively small contribution of the car traffic (8%) to the overall $PM_{2.5}$ pollution, the final air quality improvement resulting from implementing Euro 6 norm for transportation sector, is also minor.

On the other hand, Fig. 6 shows a substantial influence of the area sources on PM concentrations, especially for $PM_{2.5}$ pollution. The related emission sources come mainly from small, coal-based heating and cooking installations of the municipal sector, located mostly in the peripheral districts. This emission category is also a dominating source of SO_2 and BaP pollution in the city (Holnicki et al. 2016, 2017a, 2017b). According to recent declarations by the Warsaw authorities (UM 2020), it is planned to substantially reduce this type of coal fueled installations within the next few years. They are to be replaced with gas fueled ones or heat pumps, with additional solar panels support. When implemented, these solutions will dramatically reduce the baseline emissions (Instalreporter 2013). In addition, whenever technically possible, it is planned to connect some individual installations to the district heating network, operating in a large part of the city.

A project announcing the high refinancing of the mentioned above investments, has been launched in 2019 (UM 2020). It is the digressive plan of investments subsidizing (100% of the cost in 2019–20, 90% in 2021, 70% in 2022) aims to achieve a significant improvement in urban air quality in a short time. As a result, 800 applications have already been submitted in 2019, and a total of over 5,000 are expected by the end of 2021. Compared to the current number of 13,500 such installations in the city (Interia 2019), it means about 40% reduction in emissions from this category. Fig. 7 presents maps showing changes in PM_{10} and $PM_{2.5}$ concentrations for this case. The air quality improvement is substantial, especially for $PM_{2.5}$, mainly due to high contribution of the area sources to fine fractions of dust (compare Fig. 6).

Benzo(a)Pyrene

Benzo[a]pyrene (BaP) is one of many polycyclic aromatic hydrocarbons (PAHs) that are formed during the incomplete combustion of organic matters at temperatures between 300°C and 600°C. At the same time, it is a well-studied and most potent carcinogenic substance among the PAHs. In Poland the main source of atmospheric BaP is residential coal burning,

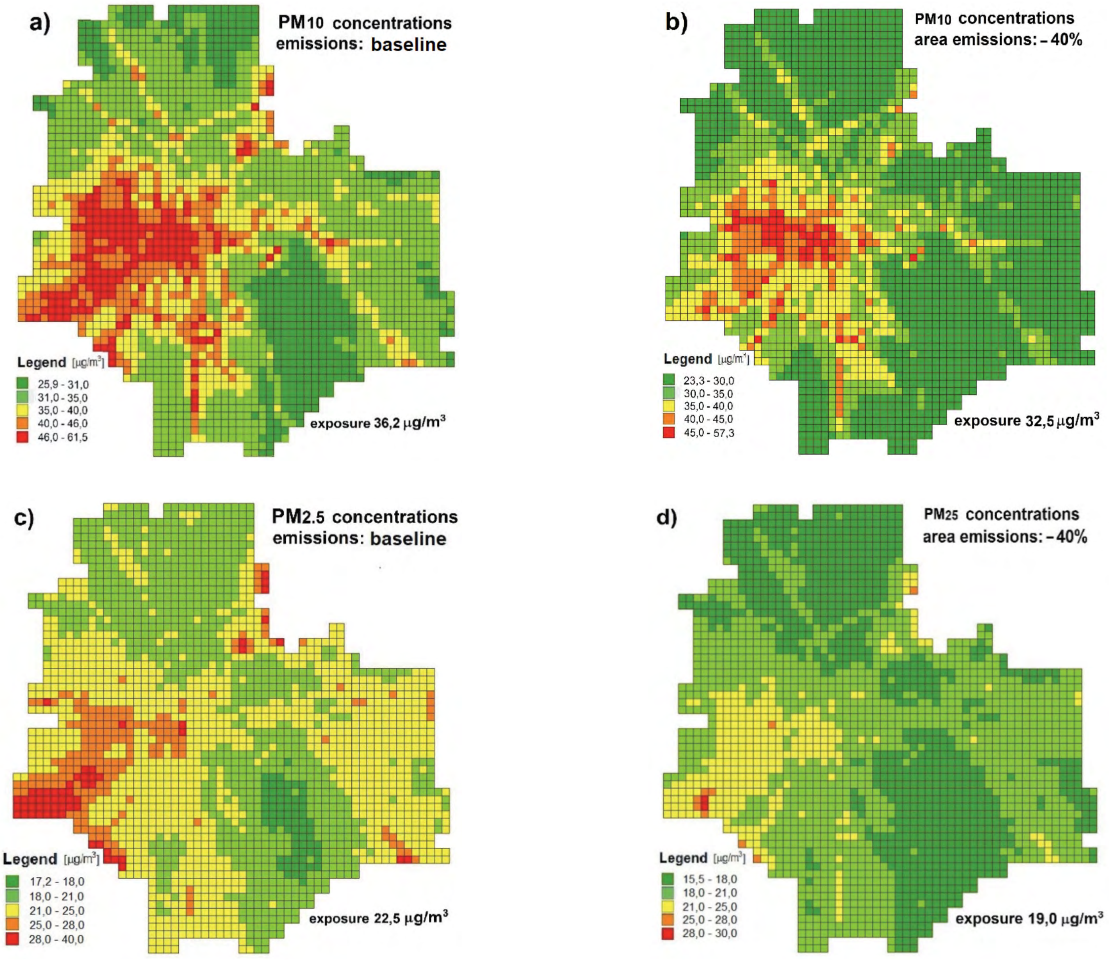

Fig. 7. Reduction of PM_{10} (a–b) and $PM_{2.5}$ (c–d) concentrations from the area emission

with some share of other organic material (wood) as well as automobile exhaust fumes (especially from diesel engines). It is confirmed by Fig. 8, which shows that in formation of high BaP concentrations in Warsaw, the surface emissions of the residential sector have a dominating share (55%), with a smaller contribution of traffic (7%).

In Fig. 9, the baseline BaP concentration map (Fig. 9a) is compared with the pollution after 40% reduction (mentioned above) of the residential area sources emission (Fig. 9b). This emission abatement implies above 25% reduction of the average BaP population exposure in the city. However, the official WHO concentration limit value (1 ng/m^3) is still exceeded in the whole urban area. This is the result of a very large external inflow of this pollution (cf. Fig. 8) from the areas adjacent to the city. A similar inflow effect relates to other pollutants depending on fuel combustion, for example, the fine fraction of particular matter, $PM_{2.5}$ or CO (Figs 4, 6).

Discussion

Two categories of emission sources are mainly discussed, those having a dominant impact on urban air pollution (Holnicki et al. 2017a): the line sources (transportation) and the surface sources (municipal sector). Air quality degradation for the baseline emission dataset is significant, and the total concentrations of NO_x, PM_{10}, $PM_{2.5}$, BaP exceed the WHO limit values, while CO limit is not exceeded.

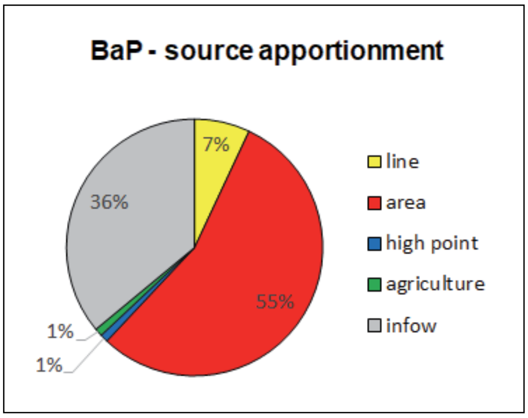

Fig. 8. Source apportionment for BaP concentrations

In Warsaw, as in other agglomerations of Eastern Europe, the car fleet has a large share of vehicles meeting only low, pre-E4 emission standards (Degraeuwe et al. 2019). The contribution of the individual car categories (diesel or gasoline) varies depending on the type of pollution. Different categories of cars dominate in each of the pollutants considered. Diesel engines have a definitely dominant contribution to NO_x emissions, while the gasoline passenger car emissions have a greatest impact on the CO concentrations (Fig. 5), while buses and other diesel cars have practically no effect on them. Hence, the modernization of passenger car fleet, particularly concerning the diesel cars, would definitely improve the city air quality, mainly due to a significant reduction of NO_x emission, and in consequence also the ozone concentration. Some administrative steps can be undertaken to regulate this, but also natural replacement of cars can help in achieving the result.

As seen in Fig. 6, cars have a considerable share in PM_{10} dust emissions, but the possible final effects of emission reduction are relatively small in this case. There are two reasons of this:

(a) application of low emission drive (also hybrid/electric) does interfere in approximately 18% of the primary car's emission, while 82% is a secondary, re-suspended fraction,

(b) only about 64% of the primary emission is due to fuel combustion, while the rest is a result of friction (cf. Table S4; WIOŚ 2012).

Thus, the implementation of any low-emission technology can result in about 2–3% reduction of the final concentration of PM_{10} pollution. The percentage share of individual fractions in $PM_{2.5}$ emission is slightly higher (Table S4), but due to the small contribution of cars in the total $PM_{2.5}$ emission (Fig. 6) the final result is similar. Hence, simulation of low-emission scenarios for PMs only results in a rather minor decrease of the related concentrations, mainly visible in the city center. However, looking comprehensively at the whole modernization of road motor vehicles, the replacement of buses with low-emission ones planned by the city authorities means a significant reduction in the emission of nitrogen oxides (NO_x), sulfur oxides (SO_x), benzene (C_6H_6), as well as – although to a lesser extent – aromatic hydrocarbons (BaP). As a result, it will undoubtedly contribute to the improvement of the city air quality.

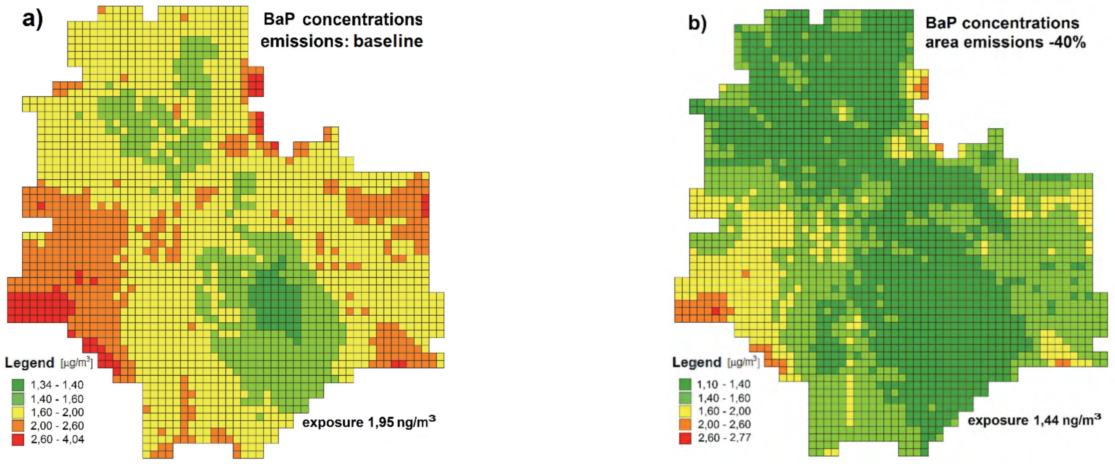

Fig. 9. Reduction of BaP concentrations related to 40% abatement of the area emission

On the other hand, the area pollution sources (mainly municipal sector) have a significant share in the overall dust concentrations, especially for $PM_{2.5}$ (46%). Here the reduction of emissions brings visible effects (Fig. 7). The implementation by Warsaw authorities of low-emission policy (modernization of furnaces, switching to gas heating, connection to the district heating network, utilizing solar energy) reduces a lot of emitted PMs. Moreover, the area sources have a dominant contribution to the emissions of polycyclic aromatic hydrocarbons (PAHs), in particular (55%) to the carcinogenic BaP, as shown in Fig. 8. Hence, the implementation of the above-mentioned emission mitigation to the area sources brings very visible effects in limiting their total concentration (cf. Fig. 9).

An interesting question is the influence of emission reduction on health. As pointed out in Holnicki at al. (2017b), $PM_{2.5}$ and NO_x are almost fully responsible for the population health risk in Warsaw, causing 98% of attributable deaths and 96% of DALYs (Disability-Adjusted Life Years). Hence, only these two pollutants are considered now: NO_x emitted by line (transportation) and $PM_{2.5}$ emitted by area (communal) sources. The modernization of passenger cars, additionally busses, and additionally trunks & vans cause, respectively, 23%, 35%, and 47% decrease of the exposure to NO_x. Proportionally, they cause, respectively, decrease of 106, 161, and 214 attributable deaths annually (out of the baseline 457); and 1664, 2521, and 3361 decrease of DALYs (out of the baseline 7170). The reduction of communal emissions causes only 16% decrease of exposure to $PM_{2.5}$, but this implies decrease of 358 attributable deaths (out of the baseline 2304) and decrease of 6304 DALYs (out of the baseline 40562). Hence, the reduction of communal emissions causes 70–80% higher improvement of health effects than the modernization of transport fleet, due to much higher impact of the former category on health. It should be noted that the discussed emission scenarios also reduce the impact of other pollutants, which, despite their smaller share, also contribute to air quality deterioration. An example is SO_2, having a minor share (below 1%) in the attributable deaths and DALYs (cf. Holnicki at al. 2017b). Since the emission structure of this pollutant is similar to $PM_{2.5}$ (51% share of the area sources, 20% inflow, 16% transport), there will be about 14% reduction of the related heath indexes due to communal emission abatement, and some additional gain (mainly in the central districts) related to transport modernization.

Conclusions

The paper analyzes several emission scenarios, the implementation of which would significantly improve air quality in Warsaw. The analysis mainly covers pollutants whose average annual concentrations exceed the WHO limit levels, but also other ones that, despite meeting the required standards, jointly contribute to the deterioration of air quality (e.g. due to the documented, negative impact on the health of residents).

This means a significant potential for improving air quality through the implementation of low-emission solutions, which is confirmed (especially in the case of NOx concentrations) by the results presented above. In the longer term, one should also take into account a definitely positive effect of the currently small but constantly growing share of the electric and hybrid cars.

The obtained results show that such far going reductions of pollutant emissions improve considerably the air quality in Warsaw but do not provide fully satisfactory results. Even the complete modernization of inhabitants' individual furnaces in Warsaw will not be sufficient to achieve the permissible level of average annual concentration of BaP required by the WHO standards. The reason is the gigantic cross-border BaP inflow. This problem is nationwide and in addition to BaP, also applies to fine fractions of particulate matter (mainly $PM_{2.5}$), but also to the carbon monoxide (CO), where the transboundary inflow has a dominant share in the overall city pollution (compare Figs 4, 6, 8). The situation in Warsaw is not too bad in this case as compared to other Polish cities, especially those located in the south of the country (EEA 2018, EEA 2019). In all these cases, however, decisions are needed at the country level, since modernization measures on the energy consumers' side, like in Warsaw, which are presented in this report, are not sufficient. A significant improvement in air quality will not be achieved without a radical change in Poland's energy mix and a decisive shift away from coal burning as the main energy source, particularly in favor of renewable energy sources (wind or photovoltaic). However, some existing energy regulations, like the so-called "10H rule" referring to wind turbines, effectively block the development of wind energy installations, despite favorable (windy) conditions in Poland and large potential opportunity for effective development of such installations.

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Supplementary material

Table S1. Euro Norms for the gasoline passenger cars (Dieselnet_LD, 2019)

emission	EURO 1	EURO 2	EURO 3	EURO 4	EURO 5	EURO 6
	[1993]	[1997]	[2001]	[2006]	[2011]	[2015]
CO [g/km]	2,72	2,2	2,3	1	1	1
HC [g/km]	–	–	0,2	0,1	0,1	0,1
NO_x [g/km]	–	–	0,15	0,08	0,06	0,06
$HC+NO_x$ [g/km]	0,97	0,5	–	–	–	–
PM [g/km]	–	–	–	–	0,005*	0,005*
PN [1/km]	–	–	–	–	–	6.0×10^{11}**

* vehicles using DI engines; 0.0045 g/km using the PMP measurement procedure

** vehicles using DI engines; 6.0×10^{12} 1/km in first 3 years from Euro 6 effective dates

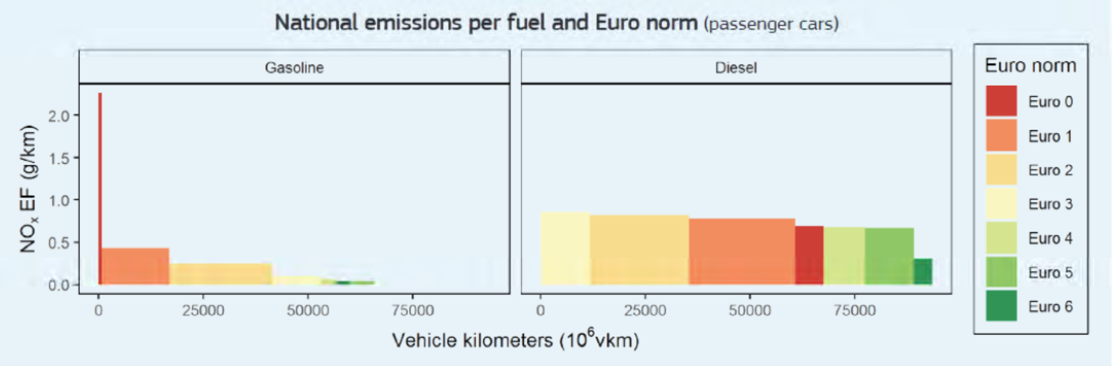

Fig. S1. Characteristics of the Euro Norms met by passenger cars in Warsaw (Degrauewe et al. 2019).
The annual emission represented by the product of: the distance driven (X-axis [km]) and emission rate (Y-axis [g/km])

Table S2. Euro Norms for the diesel passenger cars (Dieselnet_LD, 2019)

emission	EURO 1 [1992]	EURO 2 [1996]	EURO 3 [2001]	EURO 4 [2006]	EURO 5 [2011]	EURO 6 [2014]
CO [g/km]	2,72	1	0,64	0,5	0,5	0,5
HC [g/km]	–	–	–	–	–	–
NO_x [g/km]	–	–	0,5	0,25	0,18	0,08
$HC+NO_x$ [g/km]	0,97	0,7	0,56	0,3	0,23	0,17
PM [g/km]	0,14	0,08	0,05	0,025	0,005*	0,005*
PN [1/km]	–	–	–	–	$6.0\times10^{11**}$	$6.0\times10^{11**}$

* 0.0045 g/km using the PMP measurement procedure

** vehicles using DI engines; 6.0×10^{12} 1/km in first 3 years from Euro 6 effective dates

Table S3. Euro Norms for HDV diesel cars (Dieselnet_HD, 2019)

emission	EURO 1 [1992]	EURO 2 [1998]	EURO 3 [2000]	EURO 4 [2005]	EURO 5 [2008]	EURO 6 [2013]
CO [g/kWh]	4,5	4	2,1	1,5	1,5	1,5
HC [g/kWh]	1,1	1,1	0,66	0,46	0,46	0,13
NO_x [g/kWh]	8	7	5	3,5	2	0,4
$HC+NO_x$ [g/ kWh]	–	–	–	–	–	–
PM [g/kWh]	0,612	0,25	0,1	0,02	0,02	0,01
PN [1/kWh]	–	–	–	–	–	8.0×10^{11}

Table S4. Emissions of particulate matter from transportation sector in Warsaw (WIOŚ 2012)

Emission		PM_{10}		$PM_{2.5}$	
		[Mg/y]	[%]	[Mg/y]	[%]
Primary	Combustion	554	11,5	471	41
	Abrasion	308	6,5	104	9
Re-suspended		3910	81,9	566	50
TOTAL		4772	100	1141	100

Analiza scenariuszy emisyjnych w celu poprawy jakości powietrza w mieście – studium dla Warszawy

Streszczenie: Na poziom zanieczyszczenia powietrza w Warszawie wpływają głównie dwa kategorie źródeł: transport oraz sektor komunalny. Władze miasta wdrażają strategie ograniczenia emisji obu sektorów. W pracy analizowane są możliwe skutki wprowadzenia tych rozwiązań, przy wykorzystaniu metod komputerowego modelowania propagacji zanieczyszczeń. Zastosowany model, operujący na jednorodnej siatce dyskretyzacji obszaru, prognozuje stężenia średnioroczne poszczególnych zanieczyszczeń oraz ich skutki zdrowotne dla mieszkańców. Uzyskane wyniki pokazują, że planowane zmiany w sektorze transportu spowodują zmniejszenie ekspozycji mieszkańców o ok. 50% ze względu na zanieczyszczenie NO_x oraz o ok. 23% związane z zanieczyszczeniem CO. Analogiczna redukcja ekspozycji w wyniku modernizacji sektora komunalnego wynosi: 10% (PM10), 15% (PM2.5) oraz 26% (BaP). Relatywnie mniejsza redukcja zanieczyszczeń z sektora komunalnego wynika z dużego udziału napływu transgranicznego tych zanieczyszczeń z otoczenia Warszawy. Pomimo mniejszej redukcji ekspozycji, ograniczenie emisji z sektora komunalnego powoduje bardzo istotne zmniejszenie ryzyka zdrowotnego, w szczególności śmiertelności mieszkańców oraz wskaźnika DALY. Wynika to z dominującego udziału zanieczyszczeń komunalnych (np. PM2.5) w oddziaływaniu na zdrowie mieszkańców.