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The potential to improve air quality by increasing the use of deep geothermal energy

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Abstract: Increasing the use of geothermal energy may be one of the tools bringing us closer to achieving the European Commission's objective of reducing greenhouse gas emissions by 55% by 2030. Air quality improvement plays a strategic role in achieving sustainable energy development. Both European and national legislation in this field is particularly comprehensive and effective, establishing rules for monitoring and preventing air pollution in order to avoid adverse effects on human health and the environment. Unfortunately, the effective air pollutions monitoring network currently in place in Poland, with 156 monitoring stations, mainly concerns agglomerations and cities with over 100,000 inhabitants. The lack of information on the state of pollution in smaller towns is a significant limitation in terms of research aimed at assessing the effects of corrective measures taken, such as the possible transformation of district heating systems based on RES, including the use of deep geothermal energy. This paper proposes some solutions which allow the effective estimation of air conditions in locations not covered by environmental monitoring, in the context of the potential to develop geothermal resources in the rich geothermal province of Central Poland.

Keywords: air pollution, equivalent emission factors, deep geothermal energy development, emission inventory, Poland

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INTRODUCTION

The objective of this article is to develop a methodology for the rough estimation of air pollution levels in localities not covered by the environmental monitoring network. In Poland, these measurements are carried out by the Chief Inspectorate for Environmental Protection (Główny Inspektor Ochrony Środowiska – GIOŚ) in Poland, and the counterparts of the institution in other countries. Due to the fact that the measuring stations are mostly located in large cities, the precise determination of the air quality in smaller towns is difficult and is based on the need to interpolate data from the measuring stations located in the vicinity. The main aim of the article is to indicate the problem of determining air quality in smaller towns, mainly in rural areas. However, after interpreting the data on air pollution, it will also provide an indication of geothermal energy as a solution to improve air quality. The adopted methodology is based on the assumption that the distribution of air pollutants forms the so-called regional background, and local anomalies are mainly related to local conditions resulting from the presence and size of emission sources

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and overlapping topographic and climatic conditions, including anemological ones, which determine the phenomena of airing and dispersion of air pollutants (Juda-Rezler & Toczko 2016, Wierzbińska 2017, Godłowska 2019).

As regards identification of potential sources of pollution in the analysed cities, a solution based on the analysis of strategic documents in the field of energy management of self-governments/municipalities is proposed. This applies primarily to the documents which municipalities are obliged to prepare under the Energy Law. The possession of strategic documents, including those concerning the use of RES, is a prerequisite for the municipalities' ability to apply for EU funding for activities in the field of transformation towards a low-emission economy resulting from the EU's "Clean energy for all Europeans" energy policy (EC 2019).

The towns selected for analysis are located in Central Poland and are within the range of the perspective area of deep geothermal use, in particular the most abundant regional geothermal water reservoirs in Poland: Lower Jurassic and Lower Cretaceous, where it is possible to obtain geothermal waters with temperatures exceeding 50°C. In the above context, the use of geothermal energy for heating purposes offers an opportunity to improve air quality in towns where heating systems are still based mainly on fossil fuels (Berent-Kowalska et al. 2019). There are a number of reasons for this, including: favourable, confirmed geothermal conditions, possibility to use (in some places) existing heating networks, necessity to improve air quality by elimination of solid fuel boilers. The implementation of the above tasks is favoured by the social and economic environment, general public acceptance and subsidy programmes for entrepreneurs and municipalities to use geothermal resources, i.e. "Polish Geothermal Energy Plus" (NFOŚiGW 2021), funds from the Financial Mechanism of the European Economic Area 2014–2021 (EEA Grants 2019), or the priority programme "Enabling access to thermal waters in Poland" (NFOŚiGW 2020), and preferential loan schemes for geothermal boreholes for entrepreneurs, proposed by the National Fund for Environmental Protection and Water Management (Narodowy Fundusz Ochrony Środowiska i Gospodarki Wodnej – NFOŚiGW) and others.

The article also examines a methodology for comparing the condition of air pollution in the analysed locations based on the use of two synthetic indicators describing the so-called equivalent emission. This emission level was calculated due to the fact that, as can be seen in the concentration charts of single substances, it is difficult to indicate the locations where actions should be undertaken as a priority, e.g., with the use of public financial support. Equivalent emission allows one to classify all locations and indicate where the air quality problem is greatest. The results of the analyses are discussed, and the implications described in the conclusions.

BACKGROUND

Despite a number of measures taken in recent years, including the launch of its "Clean Air" programme, Poland is still one of the European countries with the worst air quality. The aim of the "Clean Air" subsidy programme (Program Czyste Powietrze 2022), the budget of which totalled 103 billion PLN for 2018–2029, is to improve air quality and reduce greenhouse gas emissions by replacing obsolete heat sources and improving energy efficiency in single-family residential buildings. From September 2018 to March 31, 2022, over 375,000 ineffective heating devices were replaced under the programme, mainly into gas stoves, biomass boilers and heat pumps.

According to a report from the European Environment Agency (EEA 2020) the country also recorded one of the lowest reductions in air pollution during the pandemic lockdown. Air pollutants caused nearly 50,000 premature deaths in Poland in 2018. Most of those – 46,300 – were caused by PM2.5. In the EU overall, PM2.5 caused the premature deaths of 379,000 people, meaning that one in eight were Polish.

Expenditures on fixed assets for the protection of air and climate in 2019 year amounted to PLN 4.1 billion (ca. € 930 million), while in 2018: PLN 2.9 billion (+41%). This is only ca. 0.2% of gross domestic product in 2019. The highest expenditures were incurred in the following voivodeships:

Mazowieckie (29.8%), Śląskie (16.4%) and Wielkopolskie (10.7%), the lowest in Lubuskie (0.7%), Kujawsko-Pomorskie (1.3%) and Warmińsko-Mazurskie (1.5%) (Górska et al. 2020).

Climate protection, implemented with the tools of the European Union's energy policy, is one of the most important challenges in Europe. The main tool for assessing the effectiveness of measures taken under the adopted strategy is the monitoring of the state of air pollution, including the level of greenhouse gases (GHG). Greenhouse gas emissions in the EU-27 decreased by 24% between 1990 and 2019 (Cappizzi et al. 2019). Adopting the "European Green Deal" means putting climate policy at the heart of the European Union's activities. Implementation of the main objective, which is to achieve climate neutrality by 2050, has led to the acceleration of the decarbonisation policy. The proposal adopted by the European Commission in September 2020 to increase the current target for reducing CO_2 emissions from 40% to 55% by 2030 will have its consequences (EU 2020). The planned share of RES has increased from 32% to 38–40% by 2030. On 14 July 2021 the European Commission adopted the above objectives as part of an extensive "fit for 55" package (RED 2021).

The targets will be met mainly by reducing the use of fossil fuels for electricity and heat generation, electrifying transport and improving energy efficiency in construction, industry and agriculture. At the end of 2016, globally, heating and cooling accounted for about 51% of final energy consumption, transport for 32%, and final electricity demand (excluding heating, cooling, or transport) for about 17% (REN21 2019).

Shallow and deep geothermal energy can play a significant role in achieving the indicated target in terms of increasing the use of RES, reducing low emissions and lowering CO_2 emissions, particularly in the heating sector. In terms of deep geothermal energy, it is particularly important to be able to use this heat source directly in place of existing heating systems.

According to the latest statistical data, about 75% of the European Union's population are urban dwellers, where dense buildings favour the distribution of heat in district heating systems (Populationof.net 2021). Furthermore, the data of Statistics Poland (Główny Urząd Statystyczny – GUS) (Berent-Kowalska et al. 2019) show that district heating heated 40.4% of all residential premises, primarily in large cities, where it was the dominant heating medium (58.3%). In addition, 31.5% of households, i.e., 78.2% of district heating consumers use water for domestic purposes (hot water). This implies the possibility of a significant reduction in the consumption of fossil fuels by using RES technologies in heating networks. Nationwide, the indoor heating and the preparation of hot water accounts for as much as 81.7% of household energy consumption, which is also a significant financial burden on households (Berent-Kowalska et al. 2019).

Unfortunately, only 66% of heat in the district heating sector is generated in Poland from cogeneration (integrated generation of electricity and heat), which is due to the low effectiveness of cogeneration support mechanisms used in the past, which has resulted in the share of heat from these units remaining unchanged for years. In addition, as many as 80% of district heating systems in Poland are inefficient (Macuk 2019). The high share of inefficient systems poses a threat to the functioning of district heating in Poland, and the legal restriction on providing state aid to inefficient district heating systems hinders their modernisation and transition to low-carbon technologies. Due to the large share of coal in heat production, the Polish district heating sector will be forced to incur ever higher costs of purchasing CO_2 emission allowances.

The statistics (Berent-Kowalska et al. 2019) show that Polish households consume 87% of the coal burnt in EU households, which directly translates into air pollution and smog formation. The main source of low emissions is the combustion of solid fuels by individuals, which accounts for 47% of PM2.5, 46% of PM10 and as much as 84% of benzo(a)pyrene (B(a)P) and other polycyclic aromatic hydrocarbons pollutants. This is also due to the fact that about 12% of the Polish population is "energy poor", i.e., has difficulty meeting its energy needs due to low income or housing characteristics.

The fact that the bad air condition is, to a large extent, caused by combustion of solid fuels, usually of poor quality, often burnt in out-of-class heating devices, is confirmed by analysis of the average monthly concentrations of B(a)P at 131 measurement stations of the Chief Inspectorate of Environmental Protection in Poland (Fig. 1).

The attached graph clearly shows that monthly exceedances of admissible value of B(a)P concentration in the air (above 1 ng/m^3) concern 7 months of the heating period, i.e., from October to March inclusive. The highest concentrations were recorded in the following months: January, February, March, when air pollution by this factor constituted 800% of the admissible standard. Both the intensity and duration of the exceedances are alarming. The poor condition of the air is also confirmed by studies of international expert groups.

The latest report of the research group Global Carbon Project (Friedlingstein et al. 2020, GCA 2020) shows that Poland is ranked 20th in the world in terms of CO_2 emissions and is the 4th largest EU Member State in the EU ranking of emitters. The "Global Carbon Project" report with emission projections for 2020 does not include a separate estimate for Poland, but according to its authors, everything indicates that CO_2 emissions will continue to rise. According to Eurostat, in 2018, in the energy sector, Poland was responsible for over 340 million tonnes of greenhouse gas emissions, with the EU28 at 3,280 million tonnes (Eurostat 2021), which accounted for over 10% of total EU28 emissions.

However, referring to the data of the European Environment Agency (EEA 2020), the average annual concentrations of air pollution in Poland were among the highest in Europe in 2018. This mainly concerns PM10 (Fig. 2) and PM2.5 (Fig. 3), and to a lesser extent nitrogen oxides (NO_x) or sulphur oxides (SO_x). This, however, does not change the fact that in the case of PM10 many measurement stations in Poland show annual average exceedances of concentrations (>40 µg/m^3). In the case of PM2.5, there are many times exceedances above 30 µg/m^3.

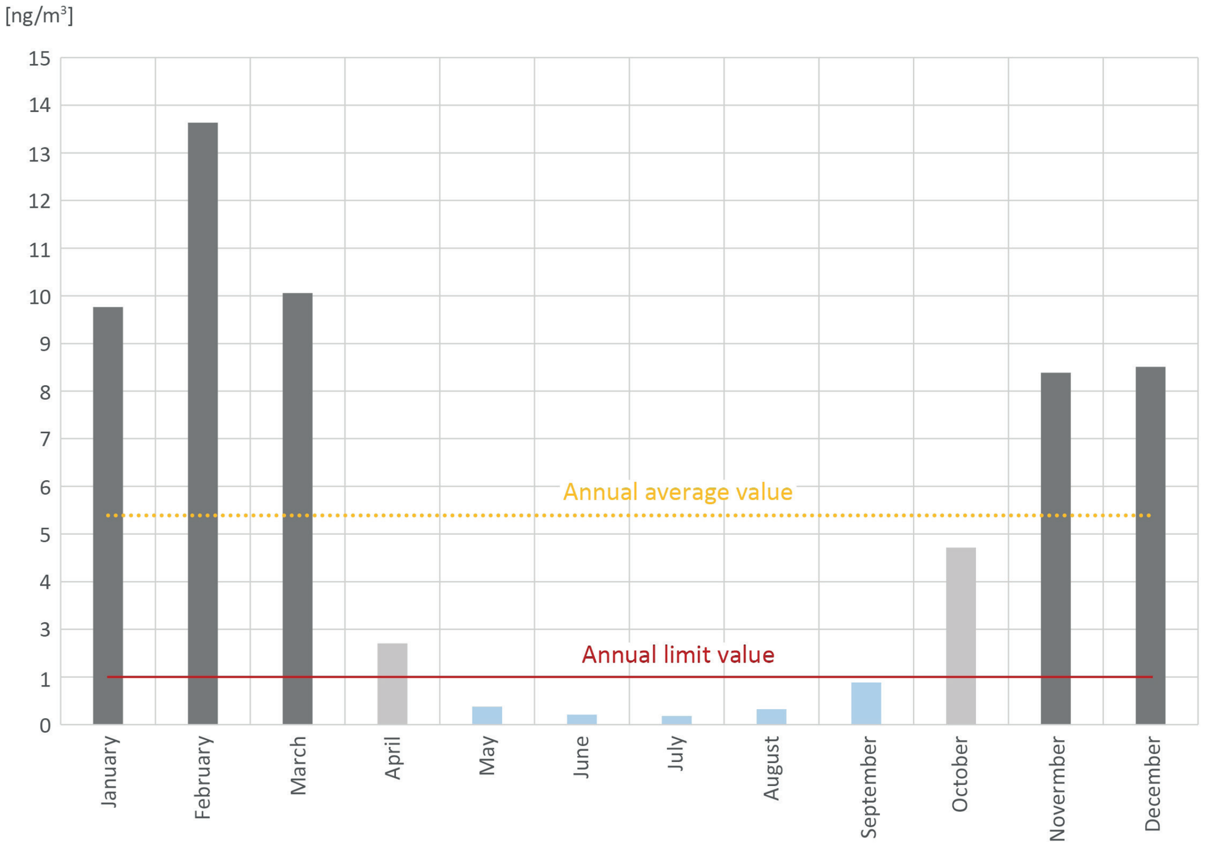

Fig. 1. *Average monthly B(a)P concentration in Poland in 2018 (based on the database of the Chief Inspectorate of Environmental Protection in Warsaw – CIEP 2021)*

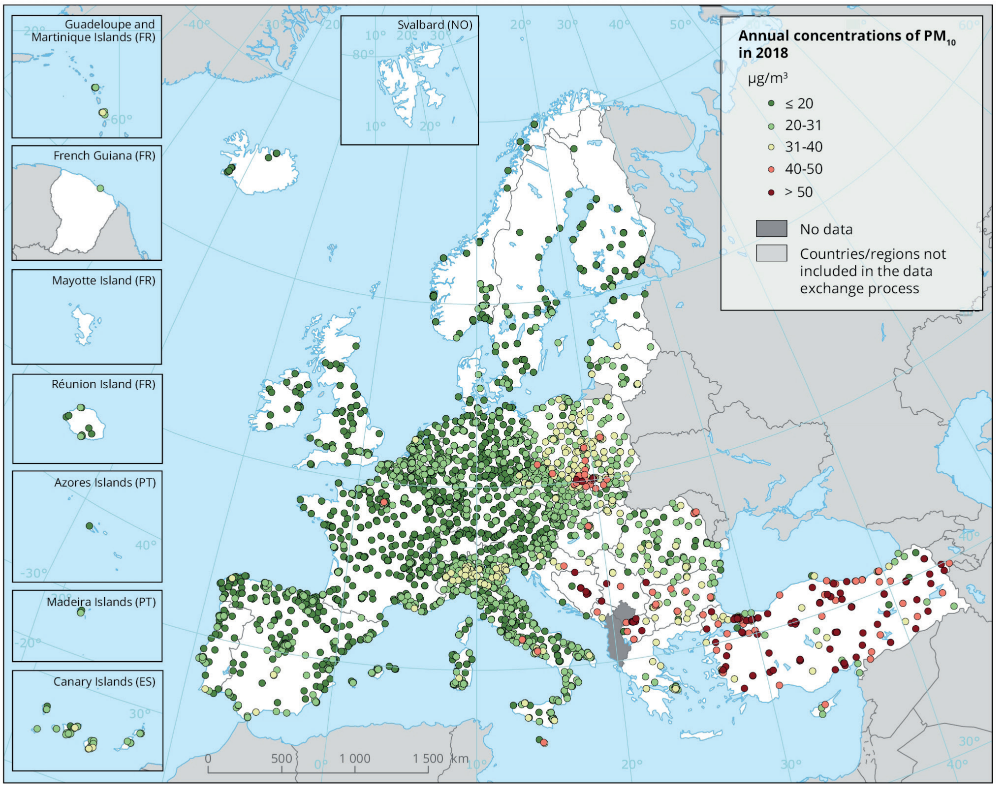

Fig. 2. *Annual limit value of PM10 concentrations in 2018 (based on EEA 2020)*

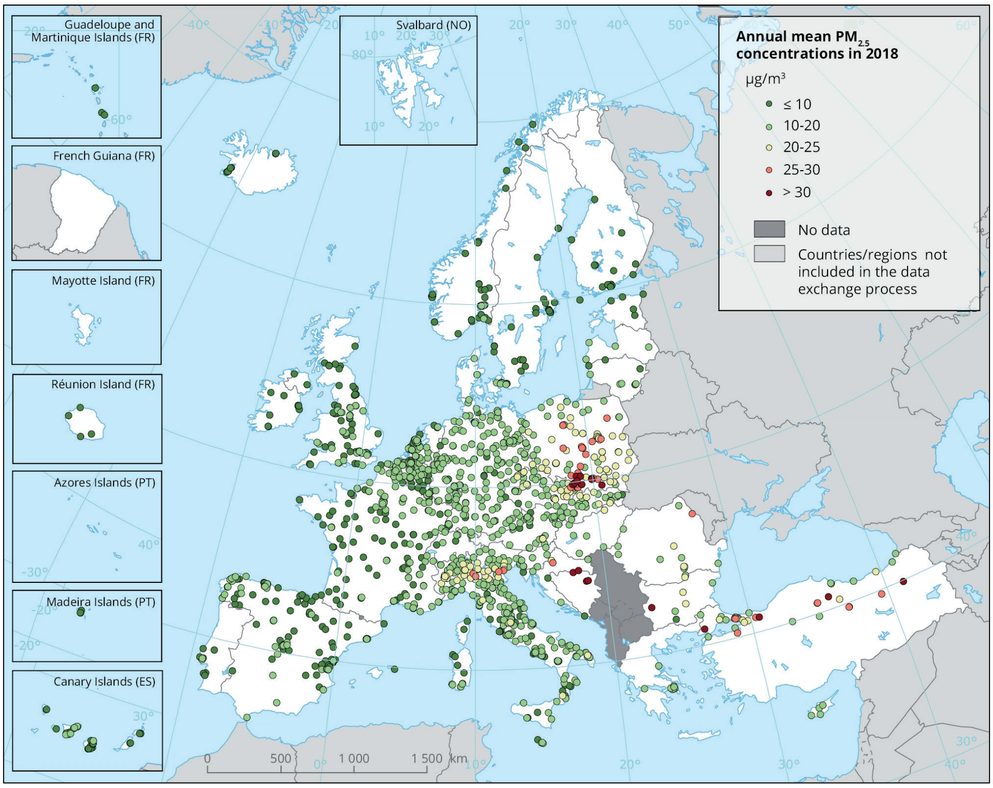

Fig. 3. *Annual limit value of PM2.5 concentrations in 2018 (based on EEA 2020)*

The situation is, however, particularly bad when analysing annual average concentrations of benzo(a)pyrene, which occurs as a result of solid fuel combustion processes (Fig. 4). The whole territory of Poland shows exceedances of average annual concentrations, unfortunately most frequently at the level above 1.5 ng/m^3 (the standard allows for 1.0 ng/m^3). In this situation, it is necessary to undertake actions which will bring specific results in both the short and long term. One such solution is undoubtedly geothermal energy.

Tools to achieve the goal of improving air quality have been developed through various scientific research projects, including "Heat Roadmap Europe: A low carbon heating & cooling strategy for Europe" (HRE 2018).

The implementation of the above assumptions in Poland is also to be supported by actions declared in government documents, including "Energy Policy of Poland until 2040", Ministry of Climate and Environment, Warsaw, 2021 (MKiŚ 2021). The government declares reduction of CO$_2$ emissions by 30% by 2030 compared to 1990 through, inter alia, 21–23% share of RES in gross final energy consumption in 2030, including a systematic growth of RES consumption in heating and cooling by 1.1%/year. In this context, the use of geothermal energy offers a wide range of perspectives, bringing Poland closer to its climate objectives on the one hand, and providing an opportunity to improve air quality in localities where district heating systems are still based predominantly on fossil fuels, on the other.

Currently, six geothermal heat plants were in operation in Poland, supplying central heating networks in Podhale and in the Polish Lowlands: in Mszczonów, Uniejów, Poddębice, Pyrzyce and Stargard.

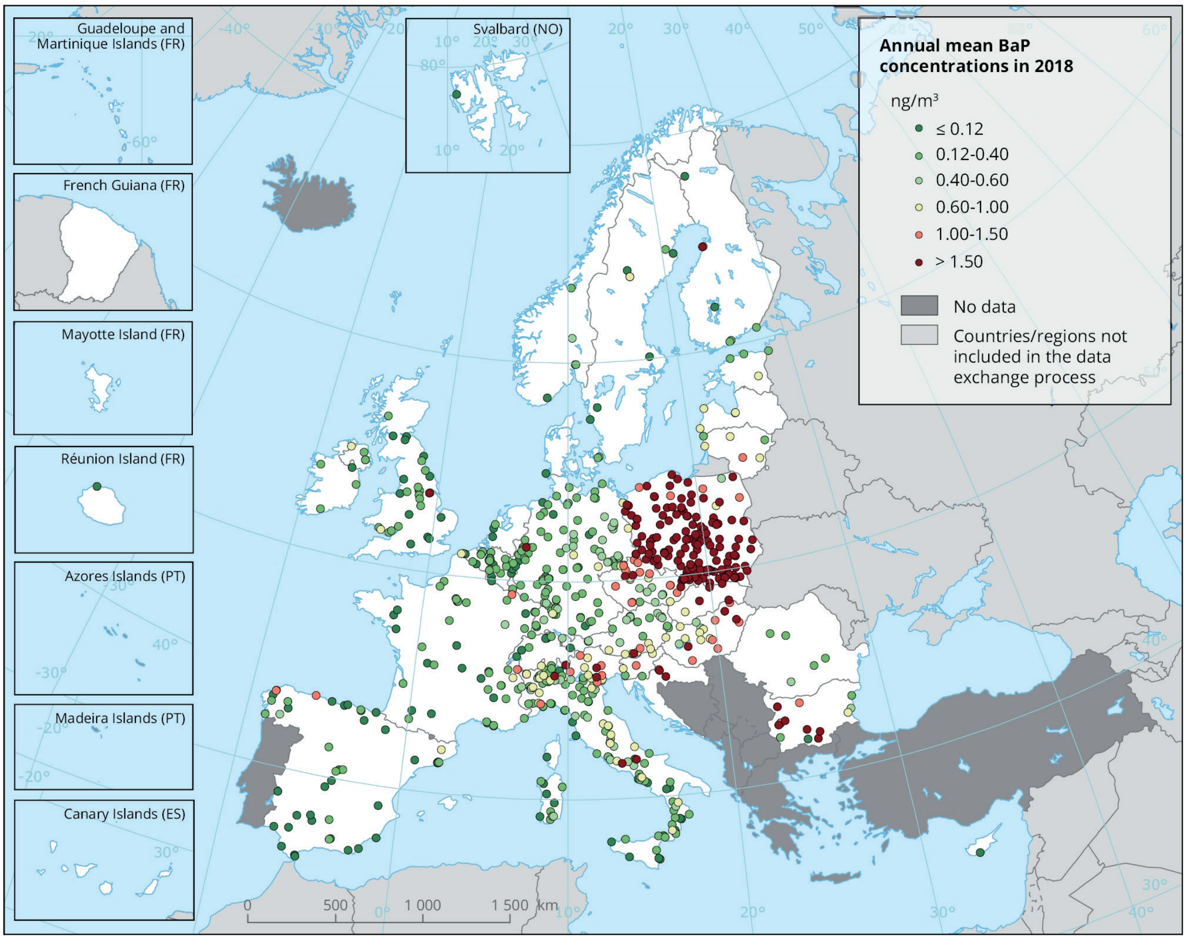

Fig. 4. Annual limit value of benzo(a)pyrene concentrations in 2018 (based on EEA 2020)

The total installed geothermal power of the 6 heat plants under consideration is almost 75 MW (personal interview with the CEOs of geothermal heating plants). Total thermal energy production at the end of 2021 was approximately 970 TJ/year.

According to the latest statistical data, provided by Statistics Poland (Brent-Kowalska et al. 2020) production of energy by carriers from geothermal sources in Poland in 2018 was 0.3%, which ranked it the last one among all RES in Poland. For comparison, the share of geothermal energy in the EU28 countries was almost tenfold higher and amounted to 2.9%. In Europe, we rank only 10th in terms of installed capacity for geothermal district heating and other direct applications (Garabetian et al. 2021).

Favourable geothermal parameters, high intake capacities, and deep-water temperatures reaching 50–90°C, particularly in Central Poland, provide opportunities to significantly increase the district heating use of geothermal waters in Poland (Hajto 2018).

The use of geothermal energy is particularly important in towns and municipalities which are still struggling with poor air quality as a result of low emissions caused mainly by the burning of solid fuels: coal, fine coal, eco-pea coal, wood, etc. Many of these locations have district heating networks based on a fine coal boiler. It is not uncommon for the existing district heating networks in these towns to cover only part of the heat and hot water demand. The remaining part of the population meets their needs for heat and hot water on their own, using individual solutions based on coal (eco-pea coal), wood pellets, natural gas, etc. Some of the consumers use RES systems (heat pumps, etc.). These are undoubtedly particularly desirable locations from the point of view of considering the use of geothermal energy (Kaczmarczyk 2018).

In this context, depending on the size of the district heating system and the parameters of geothermal water, replacing a conventional heat source or integrating the system with a geothermal source can be an ideal solution to improve the efficiency of the overall district heating system, reduce operating costs (OPEX) and reduce the local environmental load by reducing air pollution emissions (B(a)P, PM2.5, PM10 and others).

As experience has shown (Poddębice, Mszczonów and others), geothermal energy can almost completely eliminate the local combustion of solid fuels in district heating systems in some particularly favourable locations. In many cases the geothermal source could cover 100% of the demand for hot water preparation in the summer months (Kępińska 2017).

An example from the research area is a geothermal installation and district heating plant in Mszczonów, that has been successfully operating since the year 2000. Due to low salinity, the system is running with a single well, and spent fresh water is discharged into the river. The total installed capacity is 8.3 MW_t, which includes an absorption heat pump with a capacity of 2.7 MW_t, a compressor heat pump of 1.0 MW_t and a low-temperature gas boiler of 4.6 MW_t – securing consumers' heat demand during the colder periods. During the heating season approx. 40% of heat demand in the municipality is covered from a geothermal source. The geothermal heating plant in Mszczonów has replaced three municipal coal-fired boiler houses, which allowed to eliminate approx. 4,500 tonnes of previously burnt solid fuels per year. As a result, emissions of SO_2 were reduced by 100%, NO_x by 82%, CO by 98%, CO_2 by 75%, and PM10 by 100% (PSG 2021). Mszczonów, with ca. 6,500 inhabitants, is an excellent example that even a relatively small geothermal resource integrated with other efficient and ecological heat sources, together with cogeneration, can significantly contribute to the improvement of air quality – not only in the selected cities, but in the whole region as well.

Summing up, it should be said that the use of geothermal energy for heating may significantly improve air quality in many towns and municipalities in central Poland. The environmental effect will be particularly easy to achieve in small and medium sized towns, i.e., approx. 5,000–10,000 inhabitants, and even smaller ones, where the heating targets can be met by building a small geothermal source with a capacity of up to approx. 10 MW_t.

MATERIALS AND METHODS

The original data of this study, including raw and processed air pollution measurements, are available at Mendeley Data (Hajto & Kaczmarczyk 2021).

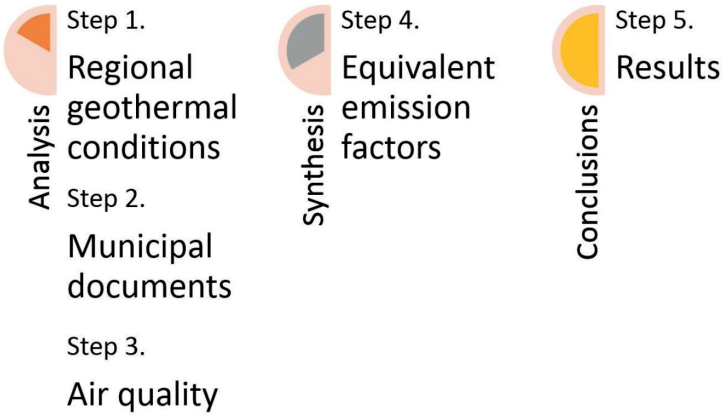

Fig. 5. *Guidelines for data acquisition, processing, and evaluation of air quality on a regional scale*

The objective of the paper was released in four stages. In the first one, 43 cities located in Central Poland were selected. The basic criterion conditioning their selection was their location. All of them are located within the range of area with confirmed favourable geological and thermal conditions which indicate possibilities of using deep geothermal resources for heating purposes. The range of this area corresponds to 50°C isotherm in the bottom of the most perspective regional geothermal reservoir on the Polish Lowlands – the Lower Jurassic aquifer. This area was delineated on the basis of results of numerous research works carried out by the AGH University of Science and Technology Team in the field of recognition of Poland's geothermal potential, including extensive monographs "Atlas of Geothermal Resources of Mesozoic Formations in the Polish Lowlands" and "Atlas of Geothermal Resources of Palaeozoic Formations in the Polish Lowlands", published in 2006 (Górecki 2006a, 2006b), and others (Hajto & Górecki 2008, Hałaj & Kępińska 2019, Sowiżdżał et al. 2020a).

It is expected that boreholes reach the geothermal reservoir of the Lower Jurassic and locally the Lower Cretaceous may yield significant stream of waters (above 100 m^3/h) at temperatures ranging 50–110°C. A simplified diagram of the work carried out is shown in Figure 5.

The second stage of work performed concerned an inventory of the local heat market, including an analysis of strategic documents in force in the region. It aimed at the initial determination of the technical possibilities of commissioning or expanding a district heating network using geothermal energy.

In the third stage, data from the Chief Inspectorate of Environmental Protection on the state of air pollution in Poland in 2018 were obtained and interpreted. It was decided to carry out the analysis with reference to the year 2018, due to the completeness of verified data on air quality, also with reference to the structure of consumption and type of energy sources used for energy purposes, both on the Polish and European scale.

As a synthesis of the air pollution data quality analysis, equivalent emission calculations were performed for the considered locations (step 4). On the one hand, it may be concluded that ranking of the considered locations with respect to particular pollutants (PM10, PM2.5, B(a)P, SO_2, NO_2, NO_x, CO), as presented in the results section, is sufficient. On the other hand, however, it does not give a clear answer to the question of in which location the air quality is objectively the best or the worst. For this reason, it was decided to calculate equivalent emissions for SO_2 and NO_2.

Step 1: Regional geothermal background of the analyzed locations and cities

Poland is characterized by significant low-enthalpy geothermal resources hosted mainly by Mesozoic sedimentary formations. The temperatures of the geothermal water intakes documented so far do not exceed 100°C (e.g., Górecki et al. 2010, Hajto & Górecki 2010a, 2010b, Sowiżdżał et al. 2020b). The highest temperature was found in the Konin GT-1 well, which was located in the area of the positive temperature anomaly shown on the map in Figure 6.

Poland's low-enthalpy geothermal resources are linked to four main hydrogeological provinces including: the Polish Lowland, the Sudetes region, the Carpathian Foredeep and the Carpathians. Distribution of geothermal potential is primarily conditioned by their deep geological structure.

The results of regional research carried out to date (e.g., Górecki 2006a, 2006b, Hajto & Górecki 2008, 2010a, 2010b) clearly indicate that the Polish Lowland Province (occupying about 87% of the Polish territory) is the most promising area for conjunctive geothermal water use, from district heating, through balneotherapy to recreation. Particularly favourable proven geothermal conditions exist in central and north-western part of the Polish Lowlands, which from the geological point of view, correspond to the main depleted structure, namely Szczecin – Mogilno – Łódź – Miechów Trough, extending NW-SE across the whole area of central Poland. Supplementary geothermal resources of central Poland are associated with the Pomerania Swell and the Warsaw Trough, adjacent to the eastern side.

The principal geothermal water resources in the Polish Lowlands are accumulated in the Lower Jurassic and Lower Cretaceous aquifers, which supply five out of six geothermal water-based heat plants currently operating in Poland (the sixth one is operating in Podhale – the Inner Carpathian Region). In the case study area, shown in Figure 6, being the subject of this article, the following geothermal district heating (GEODH) installations are operating in Pyrzyce (6 MW of installed geothermal capacity), Stargard (24 MW of installed geothermal capacity since April 2021), Poddębice (10 MW of installed geothermal capacity), Uniejów (3.4 MW of installed geothermal capacity) and Mszczonów (3.7 MW of installed geothermal capacity).

Fig. 6. Location of the selected cities against the background of prospective geothermal area in Poland (based on Szewczyk & Hajto 2022). Isolines express distribution of temperature at the base of the Lower Jurassic aquifer above the threshold value of 50°C

All these heating plants utilize geothermal water at temperatures ranging from 42°C (Mszczonów) to 83°C (Stargard). Exceptionally good geothermal conditions in the area of our interest are also confirmed by the results of the latest exploration drillings carried out in the period of 2013–2018 in Konin (2013), Koło (2017), Sochaczew (2017), Sieradz (2017), Turek (2018) and Tomaszów Mazowiecki (2018). In almost all of the boreholes drilled so far, better geothermal resources considering both the temperature and the well productivity have been found compared to those foreseen earlier in the drilling projects.

Although water temperature and yield wells are not the only factors determining the use of geothermal energy for heating purposes, it seems to be a crucial parameter when any deep geothermal district heating system is considered to be constructed. The remaining factors including water mineralization together with related corrosion and scaling phenomena can be considered only as a "technical issues" and not influence the geothermal potential itself.

A list of selected localities with information on number of inhabitants, population density and the presence of district heating networks is given in Table 1.

Neither of the above locations uses geothermal energy, although the results of the extensive regional studies mentioned in the article, including (Górecki 2006a, 2006b) and a number of publications (e.g., Hajto 2008, 2014, 2018, Hajto & Górecki 2010a, 2010b) indicate that a significant untapped geothermal potential exists in this region of Poland.

Assuming that air pollution is generated on the spot, mainly by burning solid fuels, it is essential to answer the question to what extent the use of geothermal potential can reduce emissions in the analyzed cities. Selected cities do not have detailed geothermal potential estimates, let alone a technical and economic study on the use of geothermal waters. In connection with the above, at the present stage of recognition, the estimation of the amount of emissions avoidable by launching a geothermal heating plant will concern the indicative assessment of the amount of emissions avoided in relation to estimated energy of geothermal heating plant – taking into account the so called theoretical potential (P_t).

Theoretical potential assumes that 100% of the existing energy resources will be used regardless of the technical and economic conditions. The theoretical potential is calculated for a single intake on the basis of estimated reservoir temperature (T_r) and discharge of production well (Q) in reference to an ambient temperature (T_o). The potential can be expressed by simplified formula after Górecki (2006a):

$$P_t = 0.0012 \cdot Q \cdot (T_r - T_o) \tag{1}$$

where:

P_t – thermal capacity of the well (doublet) [MW_t],
T_r – temperature of thermal waters (in the reservoir) [°C],
T_o – annual ambient temperature [°C],
Q – yield of geothermal water intake (estimated capacity) [m^3/h],
0.0012 – unit converter with the density and specific heat capacity of water [–].

The methodology of estimating the efficiency of hypothetical geothermal water intakes on a regional scale, for pore-type reservoirs on the example of the Polish Lowlands area was presented in the previously cited geothermal atlases (e.g., Górecki 2006a, 2006b, and literature therein), as well as in conference proceedings (e.g., Hajto & Górecki 2010c). Discharges of the boreholes were calculated based on classic hydrogeological equations, including the Darcy–Dupuit formula, applied for confined, unlimited extent groundwater horizon, exploited under stationary conditions. Theoretical discharge from a production well was calculated by superposition of permissible drawdown, hydraulic conductivity, and thickness of groundwater horizons.

Thermal energy was estimated taking into account energy efficiency conversion in geothermal heating plant, which was assumed at 90% and respectively its working time at 4,800 hours (the duration of the heating season in Poland). The results of the estimation of yields of production wells, together with the values of the corresponding theoretical resources – expressed with thermal capacity and thermal energy for particular localities – are presented in Table 2.

Table 1
Summary statistics of selected localities with information on presence of district heating networks

City name	Location (WGS84)		Number of inhabitants	Population density [person/km^2]	Existing district heating network
	longitude [DD]	latitude [DD]			
Biała Rawska	20.473412	51.803004	3,206	336.4	NO
Bieżuń	19.878193	52.961048	1,875	155.3	NO
Błonie	20.620071	52.197052	12,354	1,359.1	YES
Brześć Kujawski	18.897946	52.604776	4,660	661.9	NO
Chełmża	18.607689	53.187295	14,645	1,868.0	NO
Dąbie	18.823174	52.097773	2,017	229.2	NO
Drawno	15.754908	53.215682	2,307	458.6	NO
Głowno	19.720892	51.962790	14,422	726.9	NO
Golub Dobrzyń	19.056579	53.111173	12,828	1,710.4	YES
Gostynin	19.467967	52.420427	18,720	577.8	YES
Grodzisk Mazowiecki	20.632745	52.106584	30,955	2,346.9	YES
Kalisz Pomorski	15.907026	53.291936	4,399	367.8	NO
Kcynia	17.484587	52.992038	4,678	683.9	NO
Koło	18.630108	52.201111	22,227	1,604.8	NO
Koronowo	17.950134	53.324768	11,230	398.9	YES
Kostrzyn	17.221512	52.396778	9,711	1,216.9	YES
Kruszwica	18.329040	52.677277	8,926	1,344.3	YES
Kutno	19.375867	52.225711	44,513	1,325.2	YES
Lesznowola	20.914862	52.074610	25,976	374.8	NO
Łowicz	19.939348	52.104468	28,704	1,225.6	YES
Milanówek	20.671112	52.126147	16,398	1,220.1	NO
Mogilno	17.949347	52.658335	11,995	1,441.7	YES
Murowana Goślina	17.012964	52.572560	10,391	1,205.5	YES
Nekla	17.411764	52.379708	3,719	187.9	NO
Oborniki	16.811236	52.654529	18,341	1,302.6	YES
Pobiedziska	17.266856	52.477969	9,139	892.5	YES
Police	14.570792	53.565486	32,970	883.7	YES
Prażmów	21.008968	51.962063	10,804	124.9	NO
Radziejów	18.530280	52.618363	5,638	990.9	NO
Rawa Mazowiecka	20.253562	51.761848	17,480	1,224.1	YES
Sierpc	19.667012	52.853566	18,148	976.2	YES
Ślesin	20.250195	52.235077	3,135	436.6	NO
Sochaczew	19.610792	51.901190	36,790	1,404.7	YES
Stryków	18.170316	52.629671	3,493	428.6	NO
Strzelno	17.071600	52.408260	5,701	1,278.3	YES
Swarzędz	16.580952	52.610652	30,739	3,735.0	YES
Szamotuły	18.310028	52.379191	18,835	1,699.9	YES
Tarczyn	20.834593	51.987170	4,105	784.9	NO
Trzemeszno	17.819327	52.558635	7,752	1,419.8	YES
Wronki	16.379365	52.710729	11,293	1,943.7	YES
Września	17.568016	52.325889	30,279	2,378.6	YES
Zgierz	19.396999	51.857928	56,690	1,339.2	YES
Żychlin	19.623871	52.245302	8,288	954.8	YES

Table 2
Summary of selected parameters describing the theoretical geothermal potential of selected localities

City name	Temperature at the base of Lower Jurassic aquifer [°C]	Estimated yield of geothermal water intake [m^3/h]	Average annual ambient temperature* [°C]	Estimated thermal capacity of geothermal water intakes [MW$_t$]	Estimated thermal energy of geothermal water intakes [TJ/a]
Biała Rawska	70	50	7.6	3.7	58
Bieżuń	55	300	7.6	17.1	265
Błonie	60	45	7.6	2.8	44
Brześć Kujawski	65	155	7.6	10.7	166
Chełmża	70	300	7.6	22.5	349
Dąbie	105	145	7.9	16.9	263
Drawno	80	55	7.7	4.8	74
Głowno	80	115	7.6	10.0	155
Golub Dobrzyń	70	260	7.6	19.5	303
Gostynin	100	105	7.6	11.6	181
Grodzisk Mazowiecki	60	50	7.6	3.1	49
Kalisz Pomorski	55	35	7.7	2.0	31
Kcynia	65	300	7.9	20.6	320
Koło	120	165	7.9	22.2	345
Koronowo	50	300	7.9	15.2	236
Kostrzyn	55	85	7.9	4.8	75
Kruszwica	85	300	7.9	27.8	432
Kutno	95	60	7.6	6.3	98
Lesznowola	50	40	7.6	2.0	32
Łowicz	75	55	7.6	4.4	69
Milanówek	60	45	7.6	2.8	44
Mogilno	95	300	7.9	31.4	488
Murowana Goślina	60	75	7.9	4.7	73
Nekla	50	190	7.9	9.6	149
Oborniki	50	125	7.9	6.3	98
Pobiedziska	65	165	7.9	11.3	176
Police	75	300	7.7	24.2	377
Prażmów	50	40	7.6	2.0	32
Radziejów	80	245	7.9	21.2	330
Rawa Mazowiecka	60	135	7.6	8.5	132
Sierpc	60	105	7.6	6.6	103
Ślesin	110	60	7.6	5.2	81
Sochaczew	80	190	7.6	16.5	257
Stryków	80	300	7.9	35.0	544
Strzelno	105	120	7.9	6.1	94
Swarzędz	50	45	7.9	2.5	40
Szamotuły	55	160	7.9	19.6	305
Tarczyn	55	45	7.6	2.6	40
Trzemeszno	75	200	7.9	16.1	250
Wronki	60	45	7.9	2.8	44
Września	50	125	7.9	6.3	98
Zgierz	75	65	7.6	5.3	82
Żychlin	95	65	7.6	6.8	106

* According to the Polish Standard no. PN-EN 12831:2006.

Step 2: Inventory of the local heat market

The low emission assessment of municipalities was based on the analysis of strategic documents in force in the region, including the plans for heat, gas fuel and electricity supplies, air protection programmes, low emission reduction programmes and low emission management programmes. In addition, all municipalities' strategies aimed at improving air quality or increasing energy efficiency were analysed. On this basis, an inventory of the municipalities was conducted in terms of available network infrastructure (transmission networks – electricity, gas networks, district heating networks), production infrastructure (electricity, heat), energy consumers and the transport sector. The data comes from Air Protection Programs for the above-mentioned locations and directly from heating network operators. This analysis made it possible to systematise and unify data for each of the 43 municipalities.

Step 3: Analysis of air quality data

The third stage consisted in obtaining and interpreting data from the database of the Chief Inspectorate of Environmental Protection on pollutant emissions (PM10, PM2.5, B(a)P, SO_x, NO_x, NO_2, CO) in 2018. This is due to the fact that the Chief Inspectorate of Environmental Protection (GIOŚ) is responsible for monitoring and assessing air quality in Poland.

Measures taken by the Chief Inspectorate for Environmental Protection are based on criteria set out in 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, and Directive 2004/107/EC of the European Parliament and of the Council of 15 December 2004 relating to arsenic, cadmium, nickel, mercury and polycyclic aromatic hydrocarbons in ambient air. Accordingly, the air levels assessed are: SO_2, NO_2, CO, C_6H_6, O_3, PM10, PM2.5 as well as heavy metals and benzo(a)pyrene determined in PM10. The air quality assessment is conducted in 46 zones, consisting of 12 agglomerations, 18 cities of more than 100,000 inhabitants and 16 voivodeship areas which do not include the above-mentioned agglomerations and cities of more than 100,000 inhabitants (Kaczmarczyk 2015).

In the case of PM10, daily data for 156 measurement stations from the entire area of Poland were analysed. In the case of PM2.5 daily data were obtained from 65 measurement stations, for B(a)P – daily data from 131 measurement stations, for SO_2 – hourly data from 123 measurement stations, for NO_x and NO_2 – hourly data from 135 measurement stations and for CO – hourly data from 71 measurement stations (Tab. 3). The disproportion in the amount of analysed data for particular substances resulted directly from the fact that not every station measures concentrations of each pollutant. The data were systematized, and the values converted to annual average concentrations, which made it possible to create maps of pollution distribution for the whole territory of Poland.

Table 3
Summary of contaminant data quantities from measurement stations

Contaminants	**Number of measurement points used for the analysis**
PM10	156
PM2.5	65
B(a)P	131
SO_2	123
NO_x	133
NO_2	133
CO	71

The maps were calculated using the convergent interpolation algorithm with the use of Petrel E&P software. The main advantage of this method is the high processing speed (it does not sort the data and does not select samples) and the possibility of correct modelling from data with variable distribution. The resolution of the 2D regular interpolation grid (RSI) was set to 2.5 km × 2.5 km. This value allowed for reliable interpolation between the measurement points. Such a selected resolution of RSI enabled to avoid the creation of artefacts and to represent the spatial distribution of the examined parameter in a relatively correct manner. Additionally, each time the accuracy of the obtained 2D models was checked against the input data at the measurement points of the Chief Inspectorate of Environmental Protection station. The accuracy of obtained models (model accuracy, MA), defined as a module of the difference between the obtained value (grid model, GM) and the expected value (measured value, MV) did not exceed the assumed value equal to the so-called measurement significance. Measurement significance was different for individual pollutants, for example, for B(a)P: MA ≤ 0.01 ng/m^3:

$$MA = |GM - MV| \leq 0.01, \text{ for B(a)P} \quad (2)$$

Of course, due to the absence of MV, it was not possible to control model accuracy in target locations.

It is obvious that the occurrence of low emissions is of a local character, but there are no measuring stations in most of the analysed municipalities. Among the 43 towns selected for the study, direct information from measurement stations was only available in Rawa Mazowiecka, Łowicz and Kutno. The methodology of measurement data interpolation applied made it possible to estimate the air quality status in the remaining 40 locations and, consequently, to conduct complete studies. The map of distribution of variability of B(a)P air pollutants in Poland, as an annual average value, is presented in Figure 7.

The analysis of the map confirms that the mean values of B(a)P concentrations are considerably exceeded in the area constituting about 85% of the country (Fig. 7). The remaining area, constituting 15% of the surface area and with the value estimated on the basis of the planimetry of the map made, was located in the north-eastern part of Poland, in the region of Suwałki.

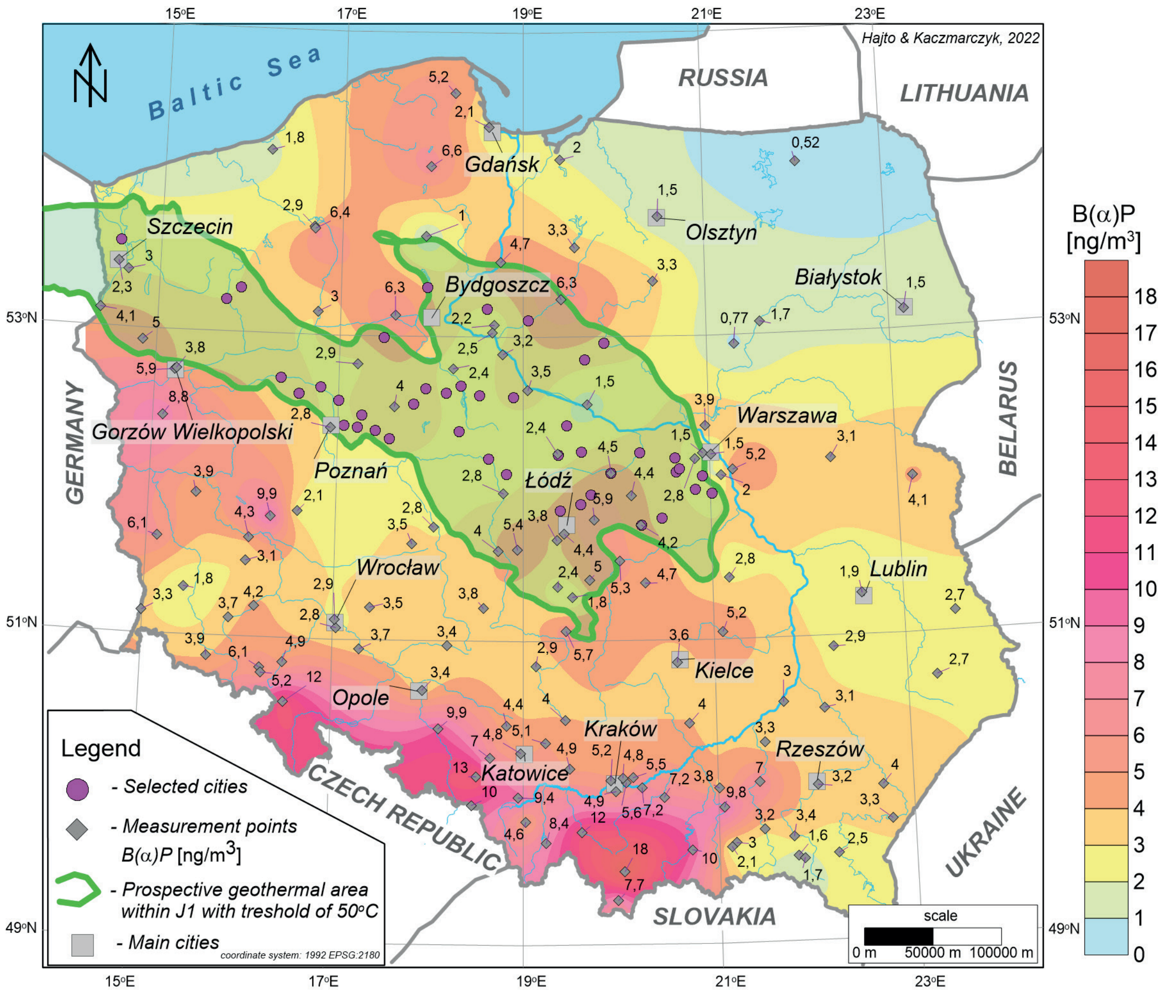

Fig. 7. Promising area of geothermal waters utilization together with the location of the city studied, against the map of B(a)P distribution in Poland (average in 2018) (based on Szewczyk & Hajto 2022)

The average annual concentration of B(a)P on the basis of data from the Puszcza Borecka measurement station located in Diabla Góra (Warmińsko-Mazurskie Voivodeship) was determined at 0.52 ng/m^3. It should be emphasised that this probably results from the specific location of the measurement station – on the edge of Borecka Forest, a place surrounded by a forest, far from dense residential buildings (Puszcza Borecka station 2021). Low annual mean value of B(a)P at the level of 0.77 ng/m^3 was found at the Guty Duże measuring station (Mazowieckie Voivodeship) – a point on the map located between Olsztyn and Białystok.

The reason for making the maps was the necessity to determine the air quality in locations without measurement stations. In such cases, use of e.g., maps developed by the European Environmental Agency (Figs. 1–4) was impossible due to the presentation of results in the form of single measurement points, and in the case of data published by the Chief Inspectorate for Environmental Protection (CIEP 2021) the problem was too low a resolution to determine air quality in a precise manner.

Stage 4: Equivalent emission as a tool to categorise municipalities in terms of air quality

The maps made at the third stage apart from visualizing the study area in terms of air pollution, made it possible to assign interpolated values to the selected localities. On this basis, each of the selected localities was assigned a value of the average annual concentration of the pollutants mentioned above, which was used to calculate the equivalent emission with reference to the SO$_2$ reference index. The calculations were made on the basis of the following formula:

$$\begin{aligned} Z_{r\mathrm{SO2}} &= Z_{\mathrm{SO2}} + Z_{\mathrm{NO2}} \times e_{\mathrm{SO2}}/e_{\mathrm{NO2}} + Z_{\mathrm{B(a)P}} \times e_{\mathrm{SO2}}/e_{\mathrm{B(a)p}} + \\ &+ Z_{\mathrm{PM10}} \times e_{\mathrm{SO2}}/e_{\mathrm{PM10}} + Z_{\mathrm{PM2.5}} \times e_{\mathrm{SO2}}/e_{\mathrm{PM2.5}} \end{aligned} \tag{3}$$

where:

$Z_{r\mathrm{SO2}}$ – equivalent emission on SO$_2$,
Z_i – emission of the i-th pollutant, where i means SO$_2$, NO$_x$, B(a)P, PM10, PM2.5,
$\mathrm{e}_{\mathrm{SO2}/ei}$ – toxicity factor of the i-th pollutant in relation to SO$_2$, where i means NO$_2$, B(a)P, PM10, PM2.5.

In addition, calculations were carried out to verify the correctness of the classification of municipalities when converting the equivalent emission to NO$_2$. Similarly, as in the case of sulphur dioxides, calculations were carried out using the following formula:

$$\begin{aligned} Z_{r\mathrm{NO2}} &= Z_{\mathrm{NO2}} + Z_{\mathrm{SO2}} \times e_{\mathrm{NO2}}/e_{\mathrm{SO2}} + Z_{\mathrm{B(a)P}} \times e_{\mathrm{NO2}}/e_{\mathrm{B(a)p}} + \\ &+ Z_{\mathrm{PM10}} \times e_{\mathrm{NO2}}/e_{\mathrm{PM10}} + Z_{\mathrm{PM2.5}} \times e_{\mathrm{NO2}}/e_{\mathrm{PM2.5}} \end{aligned} \tag{4}$$

where:

$Z_{r\mathrm{NO2}}$ – equivalent emission on NO$_2$,
Z_i – emission of the i-th pollutant, where i means SO$_2$, NO$_x$, B(a)P, PM10, PM2.5,
e_{NO2}/e_i – toxicity factor of the i-th pollutant in relation to NO$_{2,}$ where i means SO$_2$, B(a)P, PM10, PM2.5.

The same formulas ((2) and (3)) were used to determined pollutant emissions avoided.

CO was not taken into account in the formulas due to the lack of specific standards for permissible annual average concentrations. The toxicity factors of the i-th pollutant were determined on the basis of the admissible air concentrations of particular pollutants which are binding in Poland. The admissible levels of pollutants and toxicity factors of the i-th pollutant are presented in Table 4.

Table 4
Permissible contaminant levels and toxicity factors of the i-th contaminant

Contaminants	**Permissible average annual concentration e_i [µg/m^3]**	e_{SO2}/e_i	e_{NO2}/e_i
PM10	40.0	0.5	1.0
PM2.5	25.0	0.8	1.6
B(a)P	0.001	20,000	40,000
SO$_2$	20.0	0.8	1.6
NO$_x$	25.0	0.8	1.0
NO$_2$	40.0	0.5	1.0

In the case of determining the amount in the reduction of emissions of individual pollutants, the methodology proposed by KOBiZE (2015) and Kaczmarczyk (2018) was used. They were related to coal combustion on individual farms, in devices with a capacity of up to 5 MW. This is in line with the idea presented in the article, i.e., replacing individual furnaces with a geothermal heating network or increasing the power of the existing heating infrastructure thanks to the use of geothermal energy. The methodology proposed by KOBIZE and IOŚ-PIB (2015) does not take into account calculations for NO_2, PM10, and PM2.5 separately. However, it refers to suspended dust as a whole (TSP). Therefore, based on the measurement years 2010, 2018 and 2019, an aspect ratio between PM2.5 and PM10 was determined in the TSP. This coefficient was 0.56, which allowed the implementation of the methodology to determine the amount of avoided emissions in the case of PM10 and PM2.5 (Bebkiewicz et al. 2021).

RESULTS

The results of the analysis of the municipalities and their categorization from least to most polluted with PM10, PM2.5, B(a)P, SO_2, NO_x, NO_2 and CO are shown in Figures 8–14. These figures also show the potential for emissions reduction of individual contaminants.

In the case of PM10, annual average concentrations exceeding the standard of 40 μg/m^3 for the analysed locations were not indicated. Municipalities with the lowest values of concentrations below are Police (25.01 μg/m^3), Drawno (26.50 μg/m^3) and Kalisz Pomorski (26.58 μg/m^3). The highest values were indicated for Łowicz (36.81 μg/m^3), Głowno (36.46 μg/m^3), and Stryków 36.23 μg/m^3). Among the analysed group of 43 localities, 17 of them are characterized by annual average PM10 concentrations not exceeding 30.00 μg/m^3, which is 32.6%. The remaining 67.4% are values between 30.00–36.81 μg/m^3. Strzelno (130,190 Mg/year), Police (129,850 Mg/year), Mogilno (116,783 Mg/year) and Kruszwica (103,375 Mg/year) have the greatest potential to reduce PM10 emissions. The lowest potential is shown by Prażmów (7,580 Mg/year), Lesznowola (7,580 Mg/year), Szamotuły (9,473 Mg/year) and Tarczyn (9,533 Mg/year). In this situation, it is worth paying attention to the fact that the towns that have the greatest problem of PM10 air pollution do not show the greatest potential according to geothermal conditions at the same time. In the case of Łowicz it is 16,568 Mg/year, and in the case of Głowno, 37,211 Mg/year. If it is necessary to indicate locations that combine both high concentrations of PM10 in the air and the potential to limit it, the villages of Kcynia should be indicated (average annual concentrations at the level of 36.23 μg/m^3 and emission reduction at the level of 76,559 Mg/year), as well as Stryków (36.38 μg/m^3 and 61,480 Mg/year).

The highest values of annual average PM2.5 concentrations above the standard of 25 μg/m^3 are found in five municipalities. These are: Zgierz (28.65 μg/m^3), Dąbie (26.38 μg/m^3), Koło (26.00 μg/m^3), Września (25.36 μg/m^3), Kutno (25.12 μg/m^3) and Ślesin (25.11 μg/m^3). This represents 11.6% of the surveyed locations. On the other hand, only three municipalities can boast the best air quality with PM2.5 values not exceeding 18 μg/m^3, they are Koronowo (17.08 μg/m^3), Kalisz Pomorski (17.83 μg/m^3), and Kcynia (17.94 μg/m^3). As in the case of PM10 pollution, also in the case of PM2.5 the reduction potential does not correlate with annual average concentrations. The locations in the middle of the ranking have the greatest potential, i.e. Strzelno (130,190 Mg/year), Mogilno (116,375 Mg/year) and Kruszwica (103,375 Mg/year). These localities will always appear in the first three places, which results from the largest potential for geothermal heating plants, as well as the amount of energy supplied to consumers. Similarly, Prażmów, Lesznowola, Szamotuły and Tarczyn will have the lowest potential. However, the correlation between air pollution and the potential to reduce PM2.5 emissions is different. In this case, attention should be paid to Koło (26.00 μg/m^3 and 82,666 Mg/year), Ślesin (25.11 μg/m^3 and 73,010 Mg/year), and Dąbie (26.38 μg/m^3 and 62,925 Mg/year)

The analysis of annual average concentrations of benzo(a)pyrene revealed exceeding of the standard of 1 ng/m^3 in all analysed 43 municipalities. Concentrations above 5 ng/m^3 were found in four of the analysed municipalities, where the highest values are characteristic for municipalities of Stryków (5.62 ng/m$_3$), Głowno (5.41 ng/m^3), Kcynia (5.25 ng/m^3) and Bieżuń (5.20 ng/m^3). In four municipalities values not exceeding 2.00 ng/m^3 were found, although it can hardly be regarded as positive information. These are Lesznowola (1.60 ng/m^3), Gostynin (1.65 ng/m^3), Police (1.76 ng/m^3) and Prażmów (1.91 ng/m^3). Kcynia with the potential to reduce B(a)P emissions at the level of 0.2238 Mg/year and Golub-Dobrzyń with the potential of 0.2119 Mg/year are locations worth paying attention to in the context of the correlation of the highest concentrations of pollutants with the reduction of emissions.

In case of sulphur dioxide concentrations, by far the highest values of annual average concentrations were recorded in Zgierz municipality (6.36 μg/m^3). The next two places were taken by Stryków (4.80 μg/m^3) and Szamotuły (also 4.80 μg/m^3).

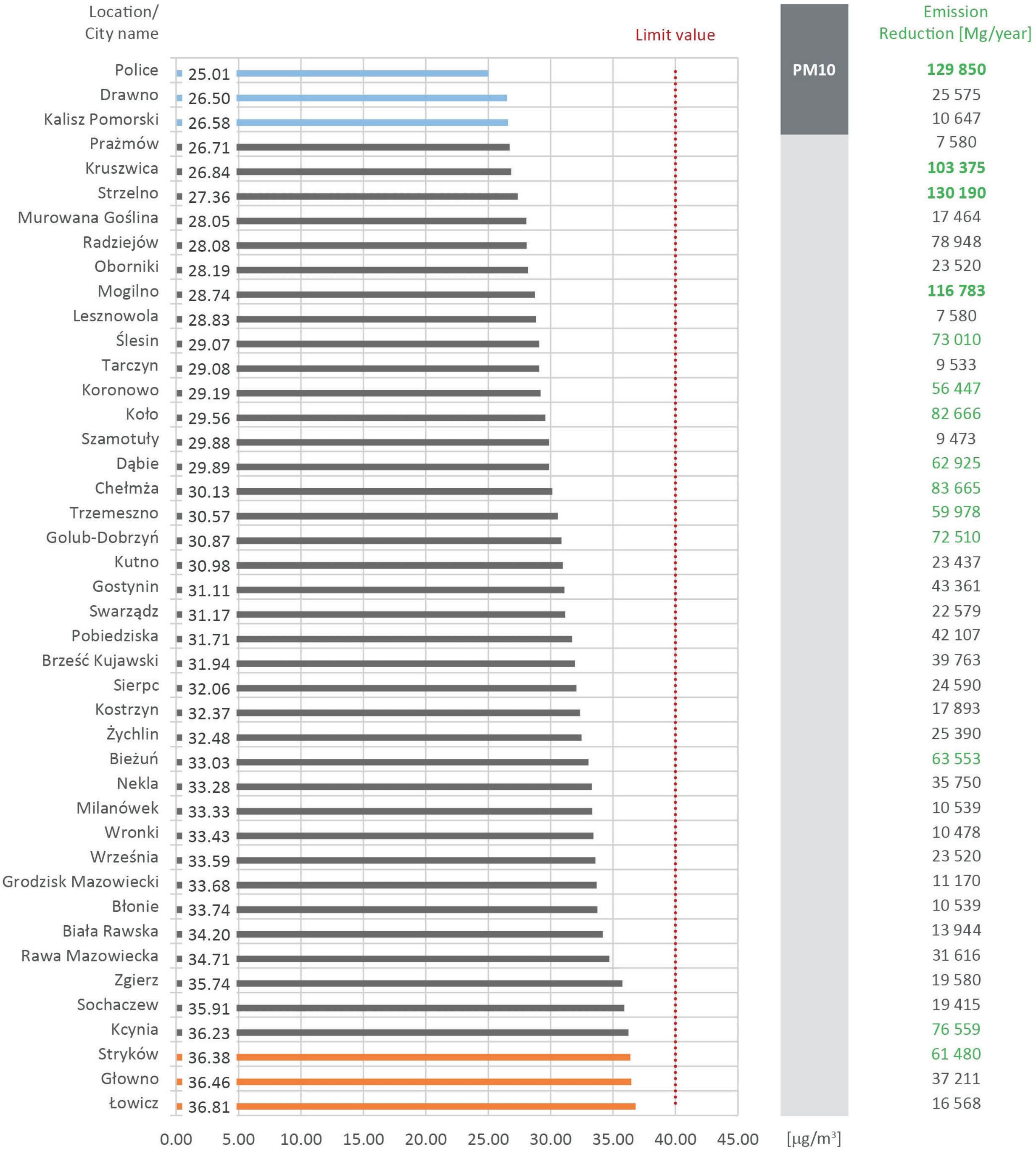

Fig. 8. *Classification of municipalities for average annual PM10 pollution in 2018*

On the other hand, by far the lowest values are characteristic for Sochaczew municipality – only 0.90 μg/m^3. Another municipality with the lowest value of SO$_2$ concentrations is Brześć Kujawski with the value of 2.07 μg/m^3 and the third place is taken by Radziejów municipality (2.39 ng/m^3). None of these values exceed the standard, however, it should be noted that in the case of influence on human health 1-hour or 24-hour concentrations are analysed.

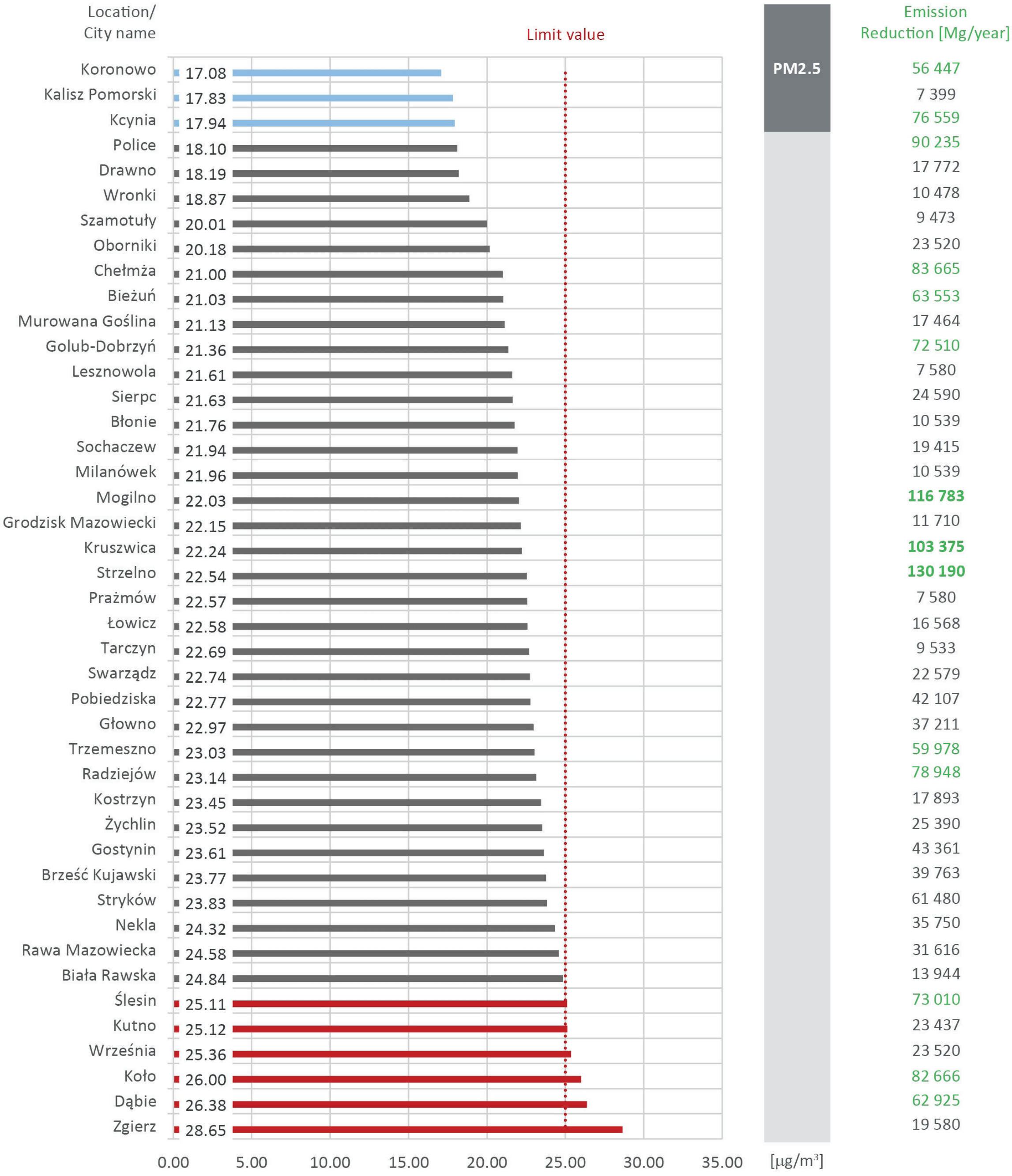

***Fig. 9.** Classification of municipalities for average annual PM2.5 pollution in 2018*

The standard for annual average concentrations of 20.00 μg/m^3 applies to the permissible levels for plant protection reasons. Among the locations that can show a correlation between the average annual concentration of SO$_2$ and the potential to reduce the emission of this particular pollutant, the following should be mentioned: Stryków (4.80 μg/m^3 and 107,188 Mg/year), Police (4.30 μg/m^3 and 157,323 Mg/year), as well as Dąbie (4.29 μg/m^3 and 109,709 Mg/year).

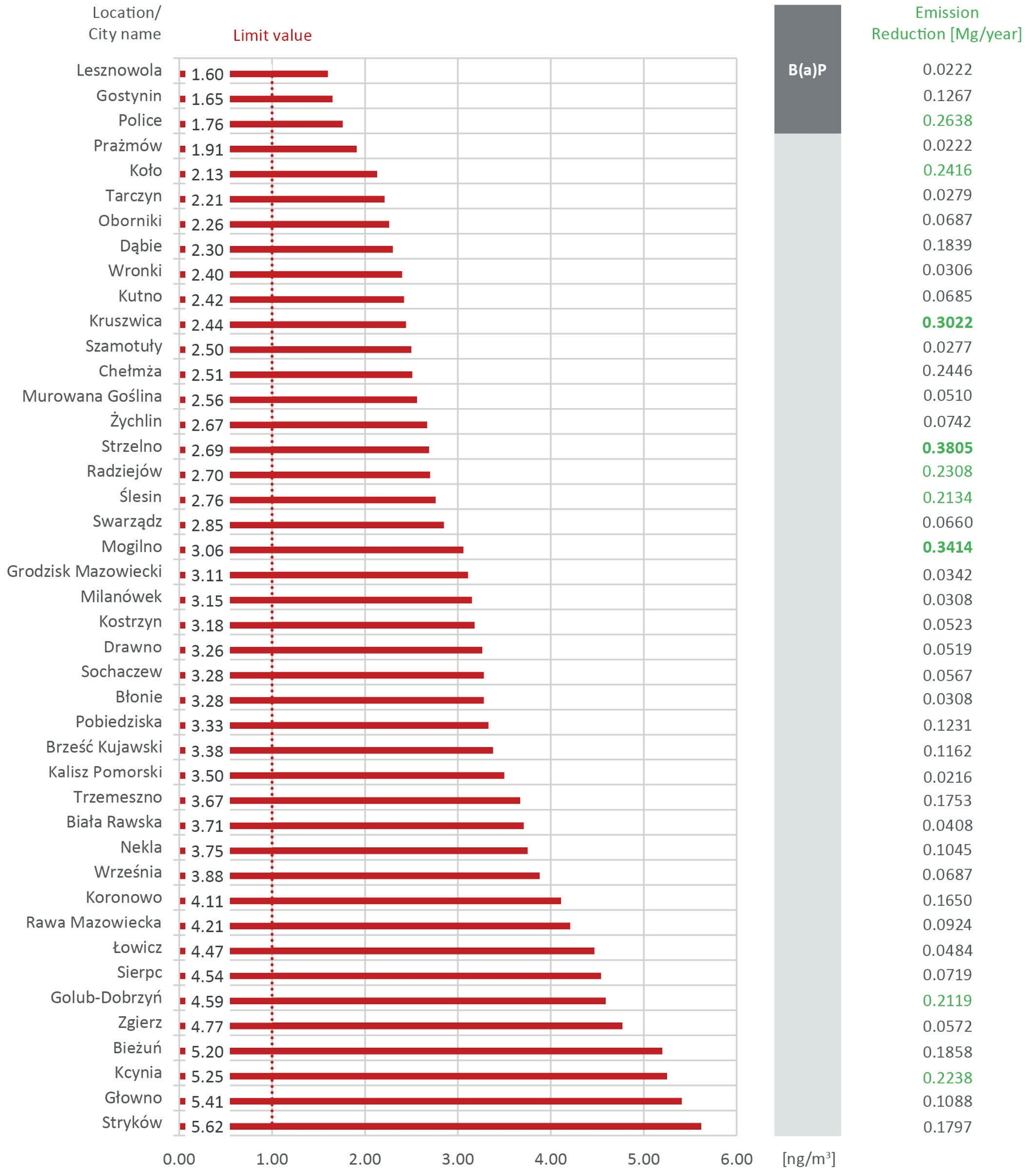

Fig. 10. *Classification of municipalities for average annual B(a)P pollution in 2018*

Regarding NO_x and NO_2 pollutants, it has to be said that the results are not the same. The standard for NO_x is 20.00 µg/m^3 and, as for sulphur dioxide, applies for plant protection. For NO_2, the annual average standard is 40.00 µg/m^3. In the first case – NO_x – as many as 24 municipalities exceeded the annual average standard, of which two show concentrations above 50.00 µg/m^3; these are Brześć Kujawski (60.97 µg/m^3) and Kcynia (57.57 µg/m^3). Close to them with 49.48 µg/m^3 is Szamotuły.

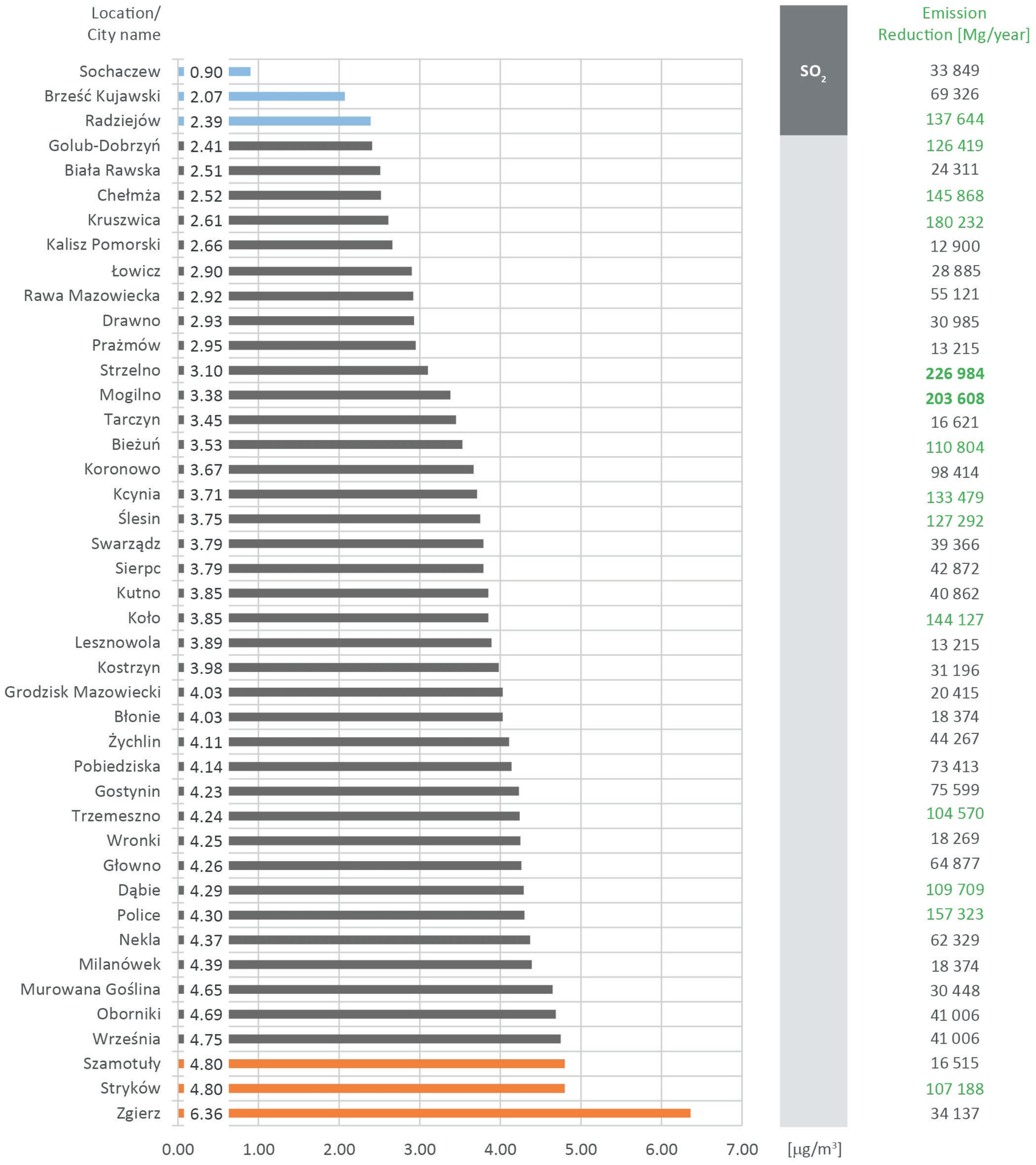

Fig. 11. *Classification of municipalities for average annual SO_2 pollution in 2018*

The most favourable are Sochaczew, Września and Śrem municipalities, but only Sochaczew can boast concentrations below 5.00–2.48 μg/m³. The highest nitrogen dioxide NO_2 concentrations were recorded for Police municipality (27.96 μg/m³). Values above 25.00 μg/m³ were reported for a total of five from the analysed municipalities. Values below 10.00 μg/m³ are again characteristic only for Sochaczew municipality (4.20 μg/m³).

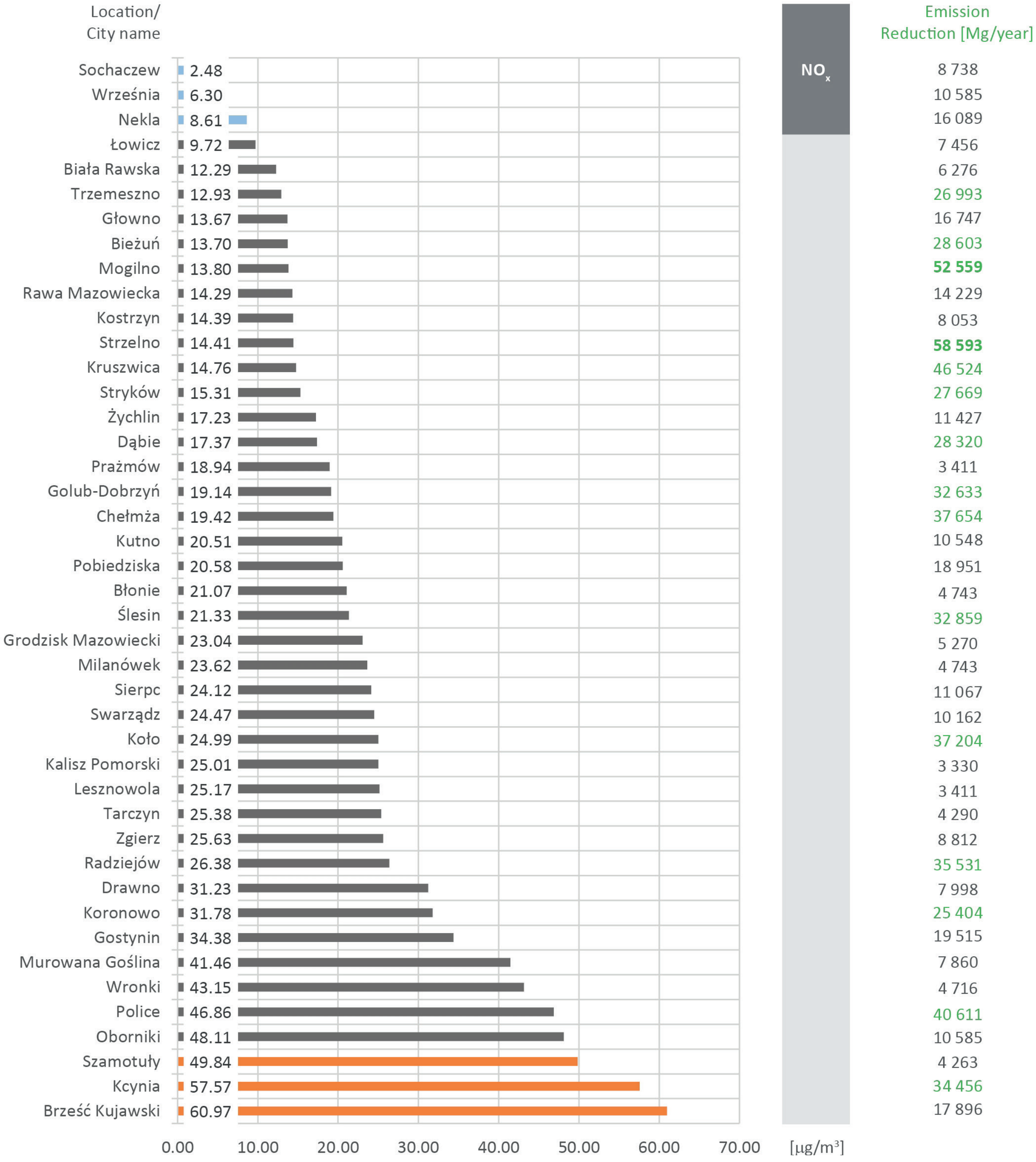

Fig. 12. Classification of municipalities for average annual NO_x pollution in 2018

None of the analysed municipalities exceeded the average annual NO_x. In the context of reducing NO_x emissions, Kcynia stands out, which ranks second among all the locations with the worst air quality for this particular substance (57.57 μg/m^3). Its potential to reduce NO_x emissions has been estimated at 34,456 Mg/year. It is also worth paying attention to Police (46.86 μg/m^3), where the potential is 40,611 Mg/year. In the case of NO_2, Poland has no methodology to determine avoided emissions.

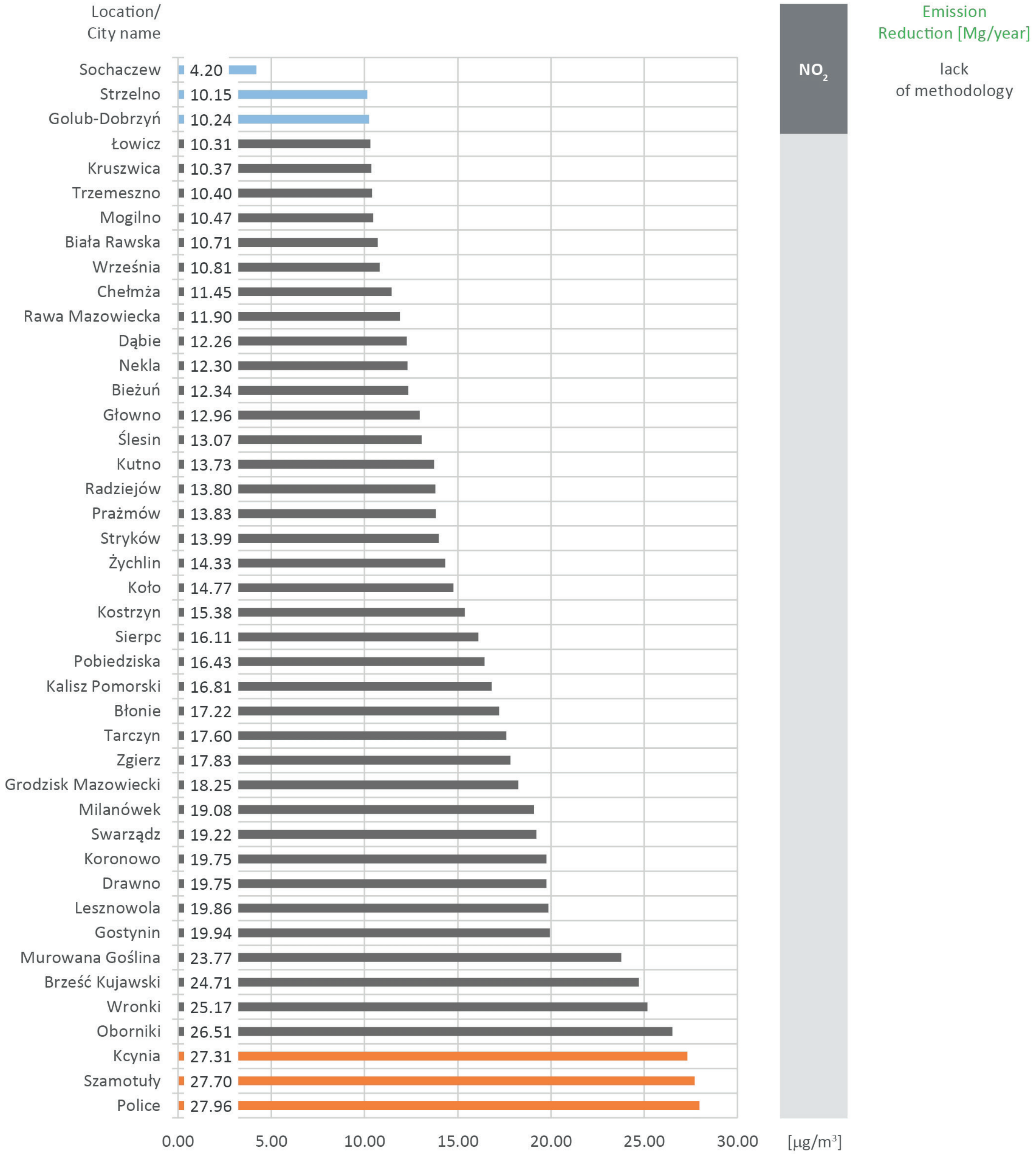

Fig. 13. *Classification of municipalities for average annual NO_2 pollution in 2018*

Among municipalities analysed for CO concentrations (no standard), values higher or equal to 0.50 mg/m^3 were recorded in three locations: Kcynia, Drawno, and Kamień Pomorski. The highest values are characteristic for the municipalities of Kalisz Pomorski (0.51 Mg/m^3), Drawno (0.50 mg/m^3) and Kcynia (0.50 Mg/m^3). On the other hand, the most favourable parameters are characteristic for the municipalities of Brześć Kujawski (0.33 Mg/m^3) as well as Bieżuń (0.34 mg/m^3) and Swarzędz (0.35 Mg/m^3).

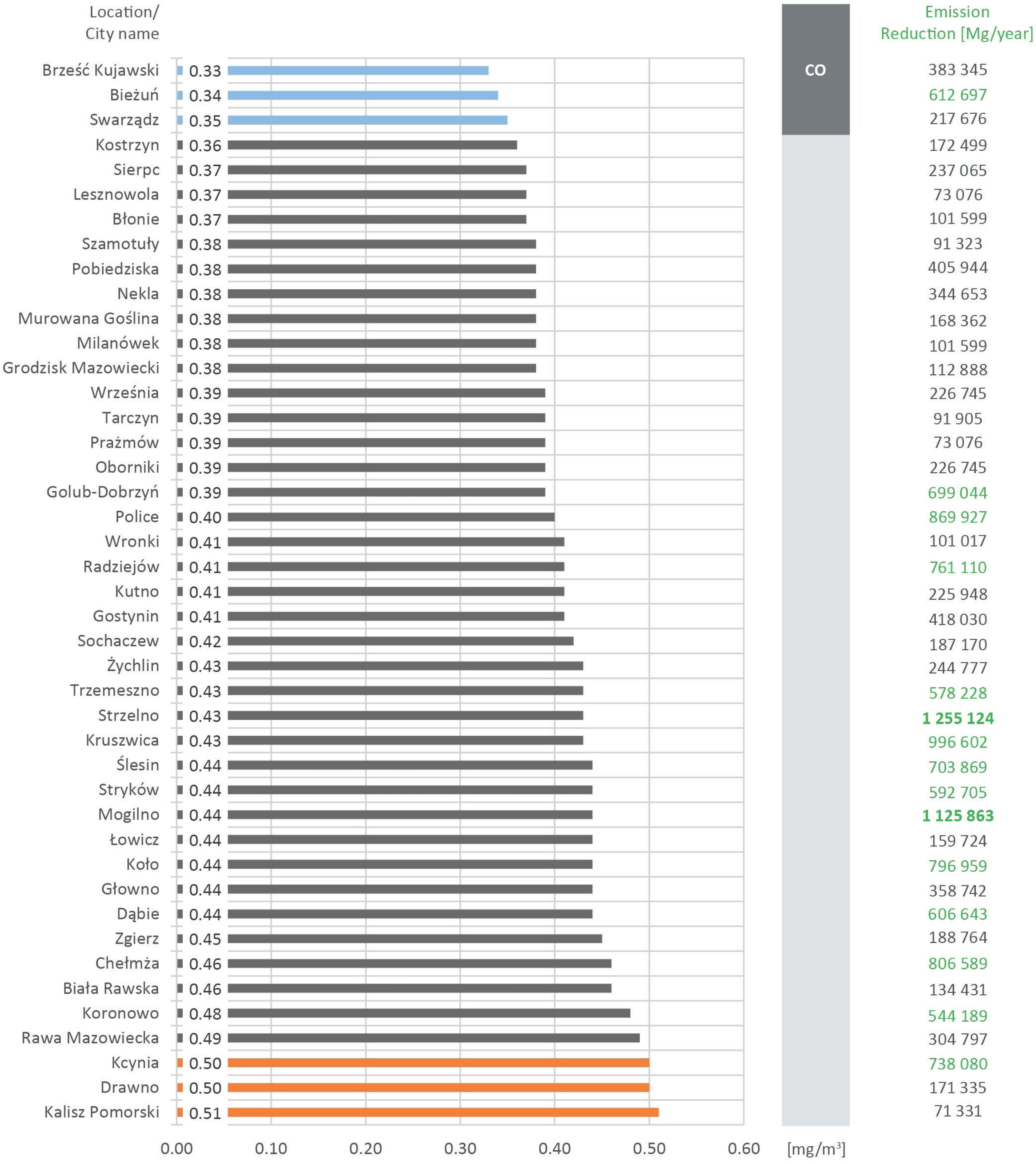

Fig. 14. *Classification of municipalities for average annual CO pollution in 2018*

The range of obtained results closes in the values 0.33–0.51 Mg/m^3). In the case of avoided emissions, Strzelno (1,155,124 Mg/year) and Mogilno (1,125,863 Mg/year) stand out. Looking for the correlation between the greatest pollution and the greatest possibility of reducing it, the towns of Kcynia (0.50 Mg/m^3 and 738,080 Mg/year) and Chełmża (0.46 Mg/m^3 and 806,859 Mg/year) should be indicated.

The results obtained for equivalent emission in two variants (for SO_2 and NO_2) are presented in Figure 15. They are identical in the sense of the classification of particular locations, indicating unequivocally where, in terms of annual average equivalent emission, the air quality was the worst. Only this analysis shows the full picture of pollutant concentrations in particular locations, not in terms of individual substances, although, of course, this aspect is equally important and, therefore, has been presented in this analysis as one of the components allowing calculation of equivalent emission.

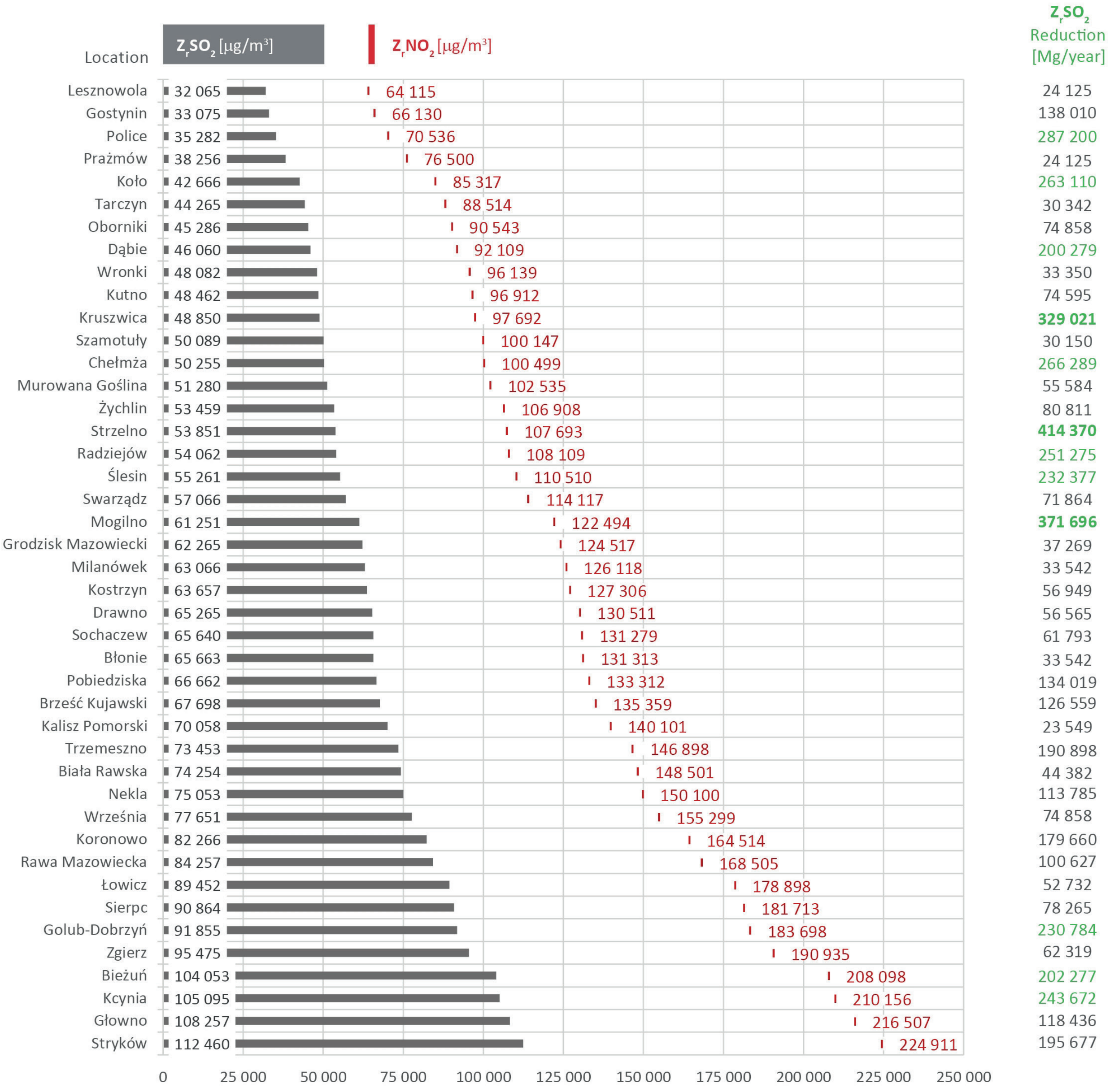

Fig. 15. Equivalent emissions of SO_2 and NO_2 for the analysed sites

By far the highest values are found in Stryków (112,460 μg/m^3 SO_2 and 224,911 μg/m^3 NO_2), Głowno (108,257 μg/m^3 SO_2 and 216,507 μg/m^3 NO_2), Kcynia (105,095 μg/m^3 SO_2 and 210,156 μg/m^3 NO_2) and Bieżuń (104,053 μg/m^3 SO_2 and 208,098 μg/m^3 NO_2. These are the only four locations with results above 100,000 μg/m^3 SO_2 and 200,000 μg/m^3 NO_2. When considering SO_2 equivalent emission, four of the considered locations were in the range of values between 100,000 μg/m^3 and 120,000 μg/m^3. In the range from 50,000 μg/m^3 to 100,000 μg/m^3 there were 28, and values below 50,000 μg/m^3 are characteristic for 11 localities.

In case of NO_2 equivalent emission analysis, numbers of localities in particular intervals are the same, but ranges differ. They are as follows: 200,000–225,000 μg/m^3 (4 locations), 100,000–200,000 μg/m^3 (28 locations), below 100,000 μg/m^3 (11 locations). The best air quality with this proposed methodology occurred in annual average in Lesznowola (32,065 μg/m^3 SO_2 and 64,115 μg/m^3 NO_2), Gostynin (33,075 μg/m^3 SO_2 and 66,130 μg/m^3 NO_2), and also Police (35,282 μg/m^3 SO_2 and 70,536 μg/m^3 NO_2).

Considering the average value of equivalent emissions for all 43 locations under consideration, which in case of SO_2 was 65,194 μg/m^3 and in case of NO_2 was 130,374 μg/m^3 it can be noticed that in both cases 20 (46.5%) locations are characterized by values exceeding the average, while 23 (43.5%) are characterized by values lower than the average. This may not be a significant disproportion, but it indicates that poor air quality in a smaller number of locations determines the possible interpretation of results averaged over the study group.

When observing the results in the context of the possibility of improving air quality, it should be noted that only the graph of equivalent emissions allows indicating the locations where the air quality is the worst and the possibilities of reducing emissions are relatively the greatest. These are the towns of Kcynia (105,095 μg/m^3 and 243,672 Mg/year), Golub-Dobrzyń (90,864 μg/m^3 and 230,784 Mg/year), Bieżuń (104,053 μg/m^3 and 202,277 Mg/year), and also Stryków (112,460 μg/m^3 and 195,677 Mg/year). On the other hand, there is, for example, the town of Police (the third in terms of the best air quality among the analysed locations – 35,285 μg/m^3), where the potential to reduce emissions is 287,200 Mg/year.

DISCUSSION AND CONCLUSIONS

In the context of the results obtained, it is important to plan specific actions for improving the quality of the environment and increasing energy efficiency in the region. The methodology presented in this paper can supplement the knowledge on air quality at the regional level, especially in locations where there are no air quality measurements.

It is certainly a challenge for the future to include in this methodology the influence of topographic and meteorological conditions, which will enable more precise calculations. Undoubtedly, further work should be directed towards more extensive numerical models. However, at this stage of advancement, being aware of further challenges, it can be concluded that the proposed methodology adds value to decision makers and stakeholders in understanding the state of local air quality. It is also important in order to understand the potential of renewable energy sources, including low enthalpy hydrogeothermal resources, to improve environmental quality as emission-free at the workplace (Kaczmarczyk 2018). It has been confirmed by Zhang et al. (2020), who, in their research, emphasise a much lower environmental impact of geothermal heating than in case of coal heating, while referring to the issue of combined heat and power generation from geothermal energy. The validity of such an approach, provided that geothermal resources with appropriate parameters (temperature, capacity of production wells) are available, is also confirmed by the research conducted by Kaczmarczyk et al. (2020c).

The results obtained clearly indicate the need for the decarbonisation of energy systems in both rural and urban areas. The public acceptance of the proposed solutions remains a question, as pointed out by, among others, Kostevšek et al. (2015), as well as Benedek et al. (2018). They agree that the focus on local energy systems and the role of renewable energy in these systems (including those based on geothermal energy) is nowadays one of the most relevant issues relating to energy policy. However, in the authors opinion, a barrier to achieving the stated goals may be the social acceptance of the proposed solutions, resulting mainly from the level of wealth in society.

In a similar context, namely the nature of the social acceptance for renewable energy, opinions are expressed by Schumacher et al. (2019). They point out that it is highly dependent on the technology in question and the experience with RES in general. It may be relevant in the future, as an interesting vision is the growth of energy autonomy of rural areas and their role as exporters of RES energy to meet the growing energy demand of urban areas (Poggi et al. 2018).

The results obtained indicate that the pursuit of such an energy model, particularly in rural areas, is an appropriate approach. These areas are characterised by a lack of centralised heating systems or access to natural gas as an energy carrier which is more environmentally friendly than other conventional fuels. Renewable energy sources are an opportunity for such areas to change their unfavourable situation, not only in the context of air quality improvement (Kaczmarczyk et al. 2020a), but in the case of geothermal energy (which can be used for recreational purposes) in order to stimulate the region's economy and increase its attractiveness to tourists (Kaczmarczyk et al. 2020b). An additional advantage of this approach to energy systems in rural areas, among other things, is that they can be used as a tool to improve energy security and support economic development (Benedek et al. 2018).

The ecological aspects of geothermal energy use are also highlighted by Soltani et al. (2021), who claim that it is an untapped potential for mitigating the effects of environmental degradation and climate change. At the same time, they rightly add that a broader context than just the ecological one should be taken into account, i.e., the economic, social or legal one. This aspect is developed by Jenniches (2018) and Frank et al. (2018), who assume that renewable energy generation is likely to be more decentralised than it is today. In the context of the region and its energy transition, the economic and social theme can therefore be expanded to include issues of employment factors and economic losses in conventional power generation industries. On the other hand, employment figures can just as well be linked to growth in the renewable energy industry, and an increasing share of RES generation in the local energy generation mix can increase the region's living comfort and energy security.

The correlation of favourable geothermal conditions in locations requiring the greatest improvement in air quality with the available energy infrastructure (mainly district heating and gas networks) and the so-called market for the thermal energy product is an issue which should be addressed in future studies.

In the context of this article, the criterion of minimum population or minimum population density was not introduced. Perhaps, however, such criteria should be taken into account in future analyses due to the issues of the economic viability of investments in the construction of a geothermal heat plant. Nevertheless, when analysing the 43 municipalities mentioned in the article, one should pay attention to the quite significant disproportions when it comes to the above-mentioned variables. For example, two locations with favourable geothermal conditions, i.e., Ślesin and Dąbie, are in the group of localities with population below 5,000. Also, the population density is not the highest (Ślesin: 3,135 inhabitants with population density of 436.6 persons/km^2; Dąbie: 2,017 inhabitants with population density of 229.2 persons/km^2). For comparison, in the group of settlements with more than 10,000 inhabitants there are municipalities with population density below 400.0 persons/km^2, these are Prażmów (124.9), Lesznowola (374.8) and Koronowo (398.9).

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