IOŚ-PIB Environmental Protection and Natural Resources
Ochrona Środowiska i Zasobów Naturalnych
sciendo
Vol. 34 No 4(98): 21-29
DOI 10.2478/oszn-2023-0019

Damian Zasina*, Iwona Kargulewicz*

$PM_{2.5}$ emission from the coal combustion in the Polish residential sector. State and outlooks

* IOS-PIB
e-mail: damian.zasina@kobize.pl

Keywords:
Air emissions, $PM_{2.5}$, emission factors, uncertainty, projections

Abstract
The paper presents obtaining the average $PM_{2.5}$ emission factor from coal combustion in the residential sector using (statistical) Monte Carlo simulation combined with the model proposed by [Lorenz 1999] and [Radović 1997], also applied by [Stala–Szlugaj 2011]. According to the results of laboratory experiments [Czaplicka et al. 2019; Shen 2014], the estimated amount of $PM_{2.5}$ released into the air from the individually heated residential sector might be underestimated. Simulated emission factor is used for estimation of the $PM_{2.5}$ emission trend for the period 1990–2018 and compared with the data provided by the official Polish emission inventory [NCEM 2020]. Due to significant changes in officially applied data (share of coal consumption and emission factor) [MCAE 2023], and to ensure the data consistency with projected fuel demand [Stala–Szlugaj 2017], and $PM_{2.5}$ emissions [MSA 2019], the older data is used [NCEM 2020] in the paper. In the near future, the next substantial changes in projected fuel use are expected due to the ongoing works on the update of the National Energy and Climate Plan.

1. INTRODUCTION

Fossil fuels are the major energy resource in the world. According to the data provided by the [World Bank 2020], the contribution of energy derived from fossil fuels was nearly 80% in 2015. The [EIA 2020] data indicates that the contribution of fossil fuels in total energy production was close to 85% in 2016, with coal as the second most important energy resource.

According to statistics provided by [British Petroleum 2019], Poland had the 10th biggest coal production in the world in 2018, and according to the official statistics [GUS 2019a–b], a significant part of produced coal (15.7%) was used for residential heating and cooking.

The coal combustion in households matters a lot for the air quality and occurrence of the low emission phenomenon in Poland [Adamczyk et al. 2017; Bogacz 2018; Dzikuć et al. 2019], especially during the winter [Juda–Rezler et al. 2020; Reizer and Juda–Rezler 2016; Rogula–Kozłowska et al. 2013]. [EEA 2019a] clearly stated that, taking into account the annual limit values for $PM_{2.5}$ particulates in European countries, bad air quality occurs primarily in Poland, northern Italy and the Balkan countries. Moreover, the Polish National Health Fund presented bad air quality as a cause of the increased number of deaths in 2017 [NFZ 2018]. The harmful effects of bad air quality are also emphasized by medical environments [Zieliński et al. 2018; FPS 2019] and the Polish Anti–Smog Movement [Burchard–Dziubińska 2019]. The reliable quantitative assessment of the $PM_{2.5}$ emissions is also very important in the context of the introduced emission–reducing policies [European Commission 2020].

Taking into account the environmental impact, the specificity of the residential sector in comparison to other sectors of the economy is its spatial dispersion (scatteredness), characteristic temporal variability (noticeably stronger during fall and winter), as well as problems with a precise estimation of the amount of particular pollutant released into the air.

This paper presents the current state of estimated $PM_{2.5}$ emissions released into the air from coal combustion in individually heated Polish households, which corresponds to the sector 1A4bi in the international NFR (or IPCC) nomenclature [EEA 2019b; IPCC 2006] as well as the projected $PM_{2.5}$ emission from the sector taking into account various data (including official) about anticipated consumption of coal in the 1A4bi sector till 2040.

2. MATERIALS AND METHODS

The emission is defined as the particular mass of the air pollutant released into the air. Estimating the $PM_{2.5}$ emission, we can consider only the primary emission, which means PM2.5 is emitted directly into the atmosphere [Klimont et al. 2017; US EPA 2019]. Methodology of emission estimation is presented widely in [EEA 2019b; Quoc Bang et al. 2019], and can be mathematically expressed as follows:

Open Access. © Author(s), published by Sciendo. BY-NC-ND This is an open access article licensed under the Creative Commons Attribution-NonCommercial-NoDerivs License (http://creativecommons.org/licenses/by-nc-nd/3.0/).

$$Ei,f,k = Af,k \times EFi,f,k, \quad (1)$$

where: $E_{k,i}$ – total emission of the pollutant *i* ($PM_{2.5}$) released into the air due to combustion of fuel *f* (coal) in source category *k* (residential sector, NFR 1A4bi); $A_{f,k}$ – activity rate, defined as the amount of energy produced as a result of combustion of the fuel *f* in source category *k*; $EF_{i,f,k}$ – emission factor for the pollutant (*i*), fuel (*f*), and source category (*k*).

The emission factor is defined as the average mass of air pollutants being produced in a particular process (including combustion). Emission factors can be obtained using various approaches: in laboratory experiments, field studies and as a result of mathematical modelling or statistical analysis e.g. [Czaplicka et al. 2019; Shen 2014; Stala–Szlugaj 2011; Shen 2015; Tian et al. 2018]. The example of the emission factors' official classification is 'Tier', presented in [EEA 2019b; IPCC 2006]. The following list details the Tiers of emission factors:

- Tier 1: default methodology using the international average values for the emission factors,
- Tier 2: using the 'country specific' emission factors (derived from the country's own studies and analysis), and
- Tier 3: based on mathematical modelling.

The presented classification of emission factors is also associated with the qualitative uncertainty class corresponding with the typical error range describing the statistical properties of considered emission factors [EEA 2019b, Chapter 5].

2.1. Activity data

Activity data for the current state emission estimations (years: 1990–2018) is derived from the [EUROSTAT 2020] database. The data about projected coal consumption for 2015–2030 is given in [Stala–Szlugaj 2017, p. 178]. There are elaborated 3 scenarios at national and regional levels: 'high' (HIGH, [Sc_WYS_GD]), 'reference' (REF, [Sc_REF_GD]), and 'low' (LOW, [Sc_NIS_GD]). For the HIGH scenario, detailed assumptions are elaborated:

- smooth changes in coal consumption, adjusted to the economic condition of Polish households,
- gradually increasing share of households using other (non–coal) energy carriers or renovated heating appliances (boilers and furnaces), and
- the decreasing consumption trend driven by the energy efficiency index for heating of the living area.

Mathematical assumptions for the elaborated HIGH scenario are given below:

- 2016–2023: –3.2% *p.a.*, due to changes in the energy efficiency index, • 2023–2027: –0.5% *p.a.*, due to replacing of the old combustion appliances, and using high quality coals, and
- 2027–2030: decline of decreasing to –0.25% *p.a.*

The LOW scenario assumes that:

- in 2030, the use of coal will be limited only to rural areas,
- from 2016, the use of coal in cities will constantly decrease,
- in the case of Polish voivodeships (provinces) that entered into force antismog resolutions is assumed the time necessary to change old boilers and furnaces, and
- newly built houses will not consume coal for heating.

The REF scenario is assumed to average between the HIGH and LOW scenarios. The original data derived from [Stala–Szlugaj 2017] are presented in Tab. 1.

The base year for enumerated scenarios is taken from Statistics Poland [GUS 2016].

Table 1. Projected coal consumption in Polish households for 2015–2030 [10^9 kg]

Scenario	2015	2020	2025	2030
HIGH	9.8*	8.5	7.8	7.7
REF	9.8*	8.4	7.4	7.0
LOW	9.8*	8.2	7.0	6.3

*) Data derived from Statistics Poland [GUS 2016] (round from 9.75).

To express the data in energy units, the average heating value for 2015 is used (25.932 MJ/kg). The time series of the energy produced from the coal combustion in the Polish households is shown in the Fig 1.

2.2. Emission factors

Currently used emission factors are derived from analysis by [Kubica, Kubica 2014] and by [Kubica, Dębski 2016], which is included in the official Polish emission inventory [NCEM 2020]. The time series for the emission factor used for the current submission is presented in Fig 2.

The time series for the emission factor is modelled using the assumptions on the coal qualitative parameters (heating value and ash content primarily) and the structure of combustion devices (furnaces and boilers) used in the buildings of the particular age.

2.3. Current emission estimations

The data collected at the CEIP official repository [NCEM 2020] can also be obtained from the [EEA 2020] repository. Apart from the officially submitted historical emissions trend, the projected $PM_{2.5}$ emissions are derived from the official 'National Energy and Climate Plan for the years 2021–2030' (NECP) [MSA 2019, Annex 2, Tab. 26, p. 30].

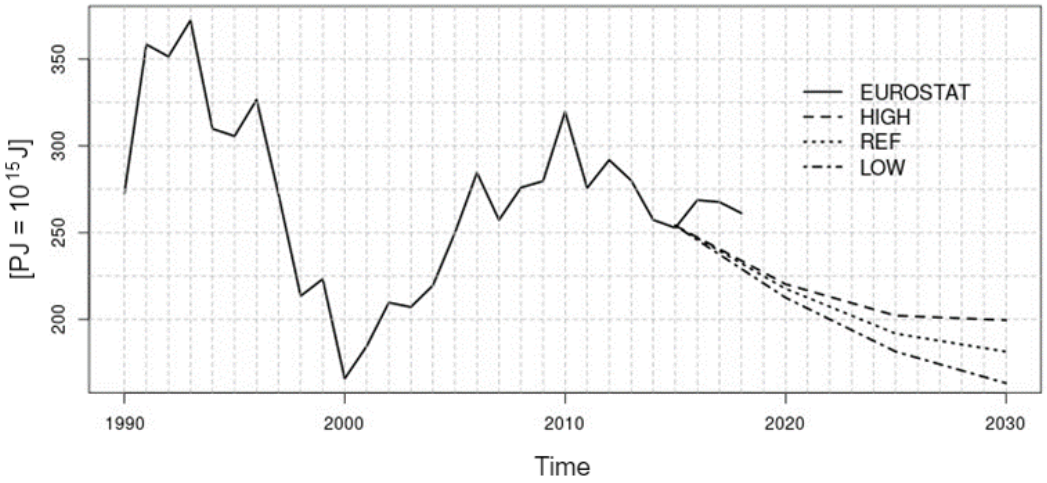


Figure 1. Coal consumption in Polish households 1990–2018. Time series: EUROSTAT – derived from [EUROSTAT 2020], HIGH, REF, LOW – based on [Stala–Szlugaj 2017]

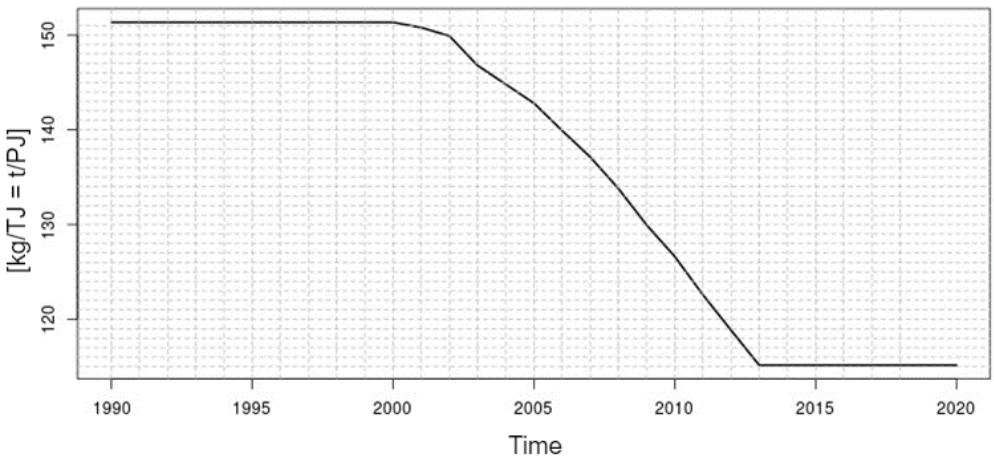


Figure 2. The time series of the $PM_{2.5}$ emission factor from coal combustion in Polish households 1990–2018 [NCEM 2020]

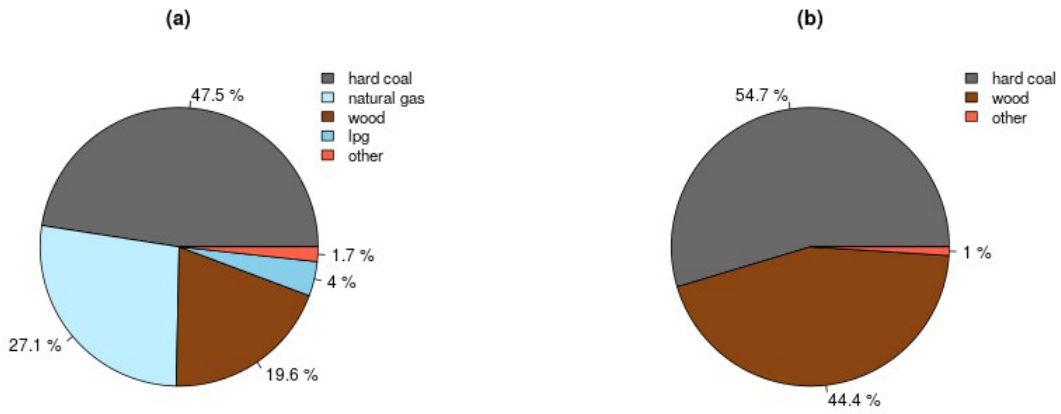


Figure 3. Data for 2018 [NCEM 2020]. (a) 'energy mix' – structure of energy obtained due to combustion of fuels in Polish households (b) 'fuel mix' – structure of the $PM_{2.5}$ emission generated by particular fuels

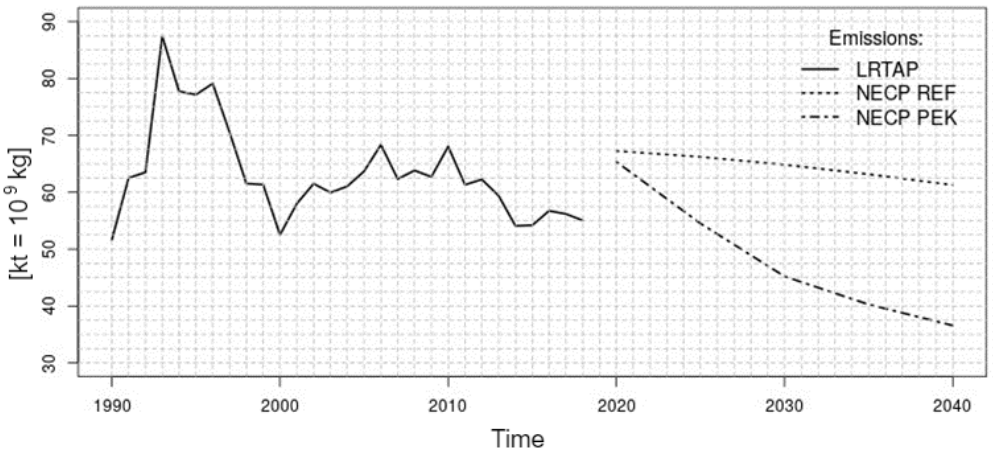


Figure 4. $PM_{2.5}$ emissions from coal combustion in Polish households 1990–2018. Time series: LRTAP [NCEM 2020], NECP REF, NECP PEK [MSA 2019]

Table 2. Parameters used for the estimation of the $PM_{2.5}$ emission factor from hard coal combustion in Polish households

Parameter	Distribution	Range	References
δ [–]	–	0.9	[Huang et al. 2014]
A [%]	$N(\mu = 5.7; \sigma = 1.5)$	[2.6; 11.0]	[Wierzchowski, Pyka 2015; GIG 2016]
Q^{PL}_t [kJ/kg]	$N(\mu = 26{,}000; \sigma = 1{,}500)$	[21,000; 31,000]	*
Q^{IMP}_t [kJ/kg]	$N(\mu = 26{,}000; \sigma = 750)$	[23,000; 29,000]	**
u_p [%]	$N(\mu = 15, \sigma = 1.5)$	[10; 20]	[Stala–Szlugaj 2011]
η_0 [%]	–	1	[Stala–Szlugaj 2011]

*) Data on coal from Polish mines. Range basing on [Stala–Szlugaj 2011], contribution – 86.7% [GUS 2017].
**) Data on imported coal. Range basing on [Stala–Szlugaj 2011], contribution – 13.3% [GUS 2017].
Q_t is obtained as weighted average from Polish and imported coal.

In the NECP report, two scenarios are taken into account: reference (REF) and introducing dedicated energy and climate policy (PEK). However, the official projections include emissions from the combustion of all fuels, including coal, wood, natural gas, fuel oils, and others (Fig. 3 (a)); the PM2.5 emission is generated mainly by the combustion of coal and wood (Fig. 3 (b)).

The time series of the PM2.5 emissions from coal combustion in Polish households (1990–2018) is presented in Fig. 4.

Taking into account the emission data is derived from the newest submission [NCEM 2020], and the official projections [MSA 2019] (Fig. 4), a vertical gap (*ca.* 10 kt of $PM_{2.5}$) can be observed. This inconsistency results mainly from the various assumptions (emission factor) used for the national emission inventory, projections, and from the discrepancy between fuels taken into account (projections also elaborated for wood combustion – see Fig. 3).

3. MODEL FOR PM2.5 EMISSION FACTOR FROM COAL COMBUSTION IN POLISH HOUSEHOLDS

3.1. Basic assumptions

The model is based on the equation given in [Radović 1997], [Lorenz 1999], and [Stala–Szlugaj 2011]:

$$EF_{\mathrm{PM}_{2.5}} = \delta \cdot \frac{A}{Q_t} \cdot u_p \cdot \left(1 - \frac{\eta_0}{100}\right) \cdot 10^7, \qquad (2)$$

where: $EF_{PM2.5}$ – $PM_{2.5}$ particulate emission factor [kg/TJ = kg $\cdot 10^{-12}$ J], δ – average content of $PM_{2.5}$ in total suspended particulates (TSP) [dimensionless], A – ash content in coal [%], Q_t – gross heating value [kJ/kg = 10^3 J/kg], u_p – particulate carriage factor [%], η_0 – dust retention in the chimney flue [%].

Detailed assumptions are presented in Tab. 2.

Table 3. The selected statistics of the simulated $PM_{2.5}$ emission factor from the coal combustion in Polish households [kg/TJ]

$\bar{x}$	σ_x	Percentiles:						
		2.5th	10th	25th*	50th**	75th***	90th	97.5th
295.1	84.6	138.6	190.6	236.4	291.5	349.8	406.3	469.3

$\bar{x}$ mean value, σ_x – standard deviation.
*) Q_1, **) *Median*, ***) Q_3.

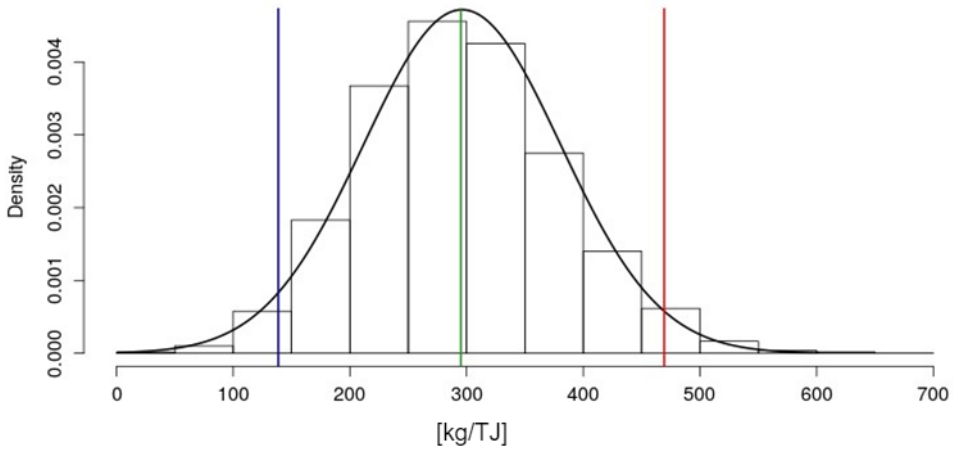


Figure 5. The $PM_{2.5}$ emission factor from coal combustion in Polish households obtained performing Monte Carlo simulation [kg/TJ]: 2.5th percentile – 138.6 (blue), median – 291.5 (green), 97.5th percentile – 469.3 (red)

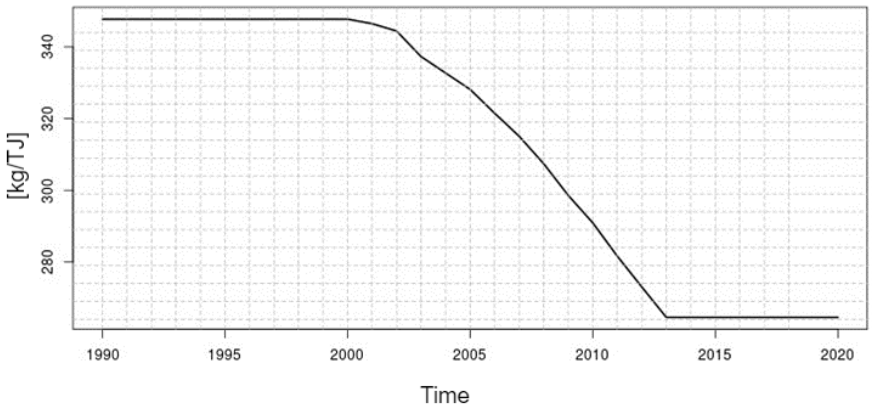


Figure 6. The recalculated time series of the $PM_{2.5}$ emission factor from coal combustion in Polish households 1990–2018

3.2. Monte Carlo simulation

The simulation is carried out for 10,000 iterations and performed in *R* [R Core Team 2020]. However, the number of iterations is assumed and suggested in various studies [Fauser et al. 2011; Lee et al. 2017; Winiwarter, Rypdal 2001; Zhao et al. 2011]. The negative results are removed from the final set. The final result is presented in Figure 5. The selected statistics of the simulated $PM_{2.5}$ emission factor from the coal combustion in Polish households are presented in Tab. 3.

The Tier 1 methodology for the emission estimation in European countries [EEA 2019b] suggests the mean $PM_{2.5}$ emission factor of 398 [kg/TJ] (95%CI: 72–480), which is very close to the model using the Monte Carlo simulation 294.5 (95%CI: 138.7–470.4) [kg/TJ]. The new study by [Czaplicka et al. 2019] proposes that the particulate matter emission factor (bituminous coal) equals 10.20 [g/kg], which corresponds to 378.5 [kg/TJ] (recalculated using the lower heating value – 26.95 MJ/kg given by [Czaplicka et al. 2019]). The range for emission factor given by [Shen 2014, p. 169] – 3.2–8.5 [g/kg] corresponds with 118.7–315.4 [kg/TJ] (recalculated using the average heating value for hard coals – 26.95 MJ/kg given by [Shen 2014, p. 48]).

On this background, the emission factors used in the currently submitted national emission inventory [NCEM

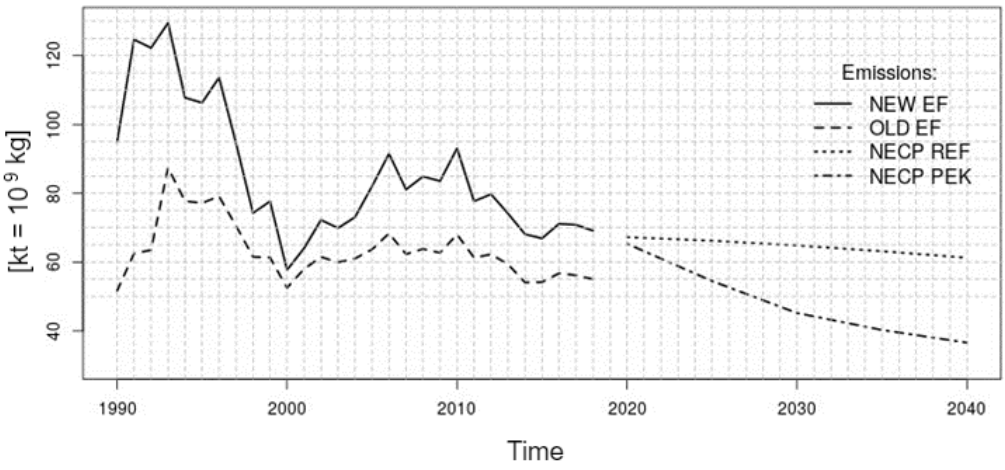


Figure 7. $PM_{2.5}$ emissions and projections from coal combustion in Polish households 1990–2040. Time series: NEW EF – New estimation calculated simulated emission factor, OLD EF – old emission factor – official submission [NCEM 2020], NECP REF – official $PM_{2.5}$ emission projection – reference scenario, and NECP PEK – official $PM_{2.5}$ emission projection – climate policy scenario

2020] (range: 115.2–151.3 kg/TJ, see Fig. 2) are very low. Assuming that the decreasing trend of the currently applied emission factor (Fig. 2) continues, representing the gradual displacement of the older boilers and furnaces, the new trend emission factor is proposed. Because the emission factors given in [Czaplicka et al. 2019; Shen 2014] are close to the upper quartile of the simulated emission factor (349.8 kg/TJ, Tab. 3), the upper quartile is used as the basic value. The new trend of the emission factor is presented in Fig. 6. It is obtained by rescaling the trend of the old emission factor (shown in Fig. 2) along with the identical trend over time.

3.3. Recalculation of the historical $PM_{2.5}$ emissions

The difference between the time series (1990–2018) is presented in Fig. 7, together with the official $PM_{2.5}$ emission projections [MSA 2019]. The $PM_{2.5}$ emissions derived from the current submission [NCEM 2020] are marked as 'OLD'. The 'NEW' time series is elaborated using the upper quartile of the new, simulated emission factor (Tab. 3). The projected emissions are shown in Fig. 7.

Analysis of Fig. 7 gives important information about potential inconsistency due to changes in the emission factor.

4. CONCLUSIONS AND RECOMMENDATIONS

1. The consistency between the data obtained from the measurements [Czaplicka et al. 2019; Shen 2019] and simulated using the model [Stala–Szlugaj 2011] is observed. In this context, the assumptions given in [Kubica, Dębski 2016; Kubica, Kubica 2014; NCEM 2020] are worth deeper investigation to better reflect the $PM_{2.5}$ emissions estimated for 1990–2018. The actual $PM_{2.5}$ emission factor from coal combustion in the residential sector may be higher than given in [NCEM 2020]. Moreover, the emission factor provided in the newest available national emission inventory [MCAE 2023] (219.45 kg/TJ) is almost 30% lower than the calculated in this paper (average value 291.5 kg/TJ). This finding is particularly important for $PM_{2.5}$ emission estimation in areas where old combustion appliances are in use. The emissions of $PM_{2.5}$ estimated particularly for years before 2000 still need more insight. The $PM_{2.5}$ emission factor obtained using the Monte Carlo simulation will be useful for the retropolation, which means reconstruction of the emission trends for previous years.
2. The results of laboratory studies [Czaplicka et al. 2019; Shen 2019] suggests that the currently used $PM_{2.5}$ emission factors in official reports [NCEM 2020; MCAE 2023] could be underestimated. It may suggest providing a status quo analysis using the newest available data, including those obtained from the necessary literature review. Apart from using the newest available data on the fuel quality, scientists and policymakers should also pay attention to the historical trends. Using statistically simulated emission factors, and information about the gradual technical development of domestic combustion appliances, combined with the Monte Carlo techniques can be used for deep analysis of both: historical and projected data.
3. The question of the approximate real trend of the $PM_{2.5}$ emission factor for coal combustion in Polish households is still unsolved. It might be possible that the trend that 'better' reflects the gradual renewal

of domestic furnaces, and then – the $PM_{2.5}$ emission should be investigated using more advanced methods such as dedicated backward analysis prepared from the perspective of the current state (retropolation).

DISCLAIMER

The findings, interpretations, and conclusions expressed in this paper are those of the authors, and not necessarily of the organization with which the authors are affiliated or official position of the Polish Government.
The condensable fraction in particulate matter is not taken into consideration in the analysis.
The article does not include data after the recalculation of statistical household balances carried out in 2022 (covering the period since 2018). This is because the data from the recalculation are not consistent with previous historical data and with available projected data. Furthermore, the process of recalculation of data is still ongoing and will take into account other source material, i.e. the results of the National Population and Housing Census 2021. An update of the official national energy projections is also planned, as the current official data in this regard is the data from the National Energy and Climate Plan for the years 2021–2030 submitted to the European Commission in 2019. After the indicated updates, the data will be available (expected no sooner than the end of 2024) that can be used to update the analyses in the article and publish an update of the article, based on the new available data.

REFERENCES AND LEGAL ACTS

ADAMCZYK J., PIWOWAR A., DZIKUĆ M. 2017. Air protection programmes in Poland in the context of the low emission, Environmental Science and Pollution Research 24 16316–16327. doi:10.1007/s11356-017-9233-9.

BOGACZ P. 2018. Proposition of changes in the law governing the combustion of solid fuels in individual energy source used by households in Poland in terms of maximizing environmental, social and economic effects, Journal of the Polish Mineral Engineering Society 1(41) 195–202. doi:10.29227/IM-2018-01-31.

British Petroleum. 2019. BP Statistical Review of World Energy June 2019. https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html.

BURCHARD-DZIUBIŃSKA M. 2019. Air pollution and health in Poland: anti-smog movement in the most polluted Polish cities, economics and environment 2(69) 76–90. doi:10.34659/dc9e-jf91.

CZAPLICKA M., CIEŚLIK E., KOMOSIŃSKI B., RACHWAŁ T. 2019. Emission factors for biofuels and coal combustion in a domestic boiler of 18 kW, atmosphere 10 (771) 1–12. doi:10.3390/atmos10120771.

DZIKUĆ M., PIWOWAR A., DZIKUĆ M. 2019. Problems of low emission in Poland in sectoral terms, in: IOP Conference Series: Earth and Environmental Science 322. doi:10.1088/1755-1315/322/1/012009.

EUROPEAN COMMISSION. 2020. Report from the Commission to the European Parliament and the Council on the progress made on the implementation of Directive (EU) 2016/2284 on the reduction of national emissions of certain atmospheric pollutants, report No. COM/2020/266 final. https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1593765728744&uri=CELEX:52020DC0266.

EEA. 2019a. Air quality in Europe — 2019 report. doi:10.2800/82235.

EEA. 2019b. EMEP/EEA Air Pollutant Emission Inventory Guidebook 2019. doi: 10.2800/293657.

EEA. 2020. EIONET Central Data Repository. http://cdr.eionet.europa.eu/pl/eu/nec_revised/inventories/envxo7afa/.

EIA (U.S. Energy Information Administration). 2020. Total Energy Production. https://www.eia.gov/international/data/world.

EUROSTAT. 2020. The Database of European Statistical Data. https://ec.europa.eu/eurostat/data/.

FAUSER P., SØRENSEN P., NIELSEN M., WINTHER M., PLEJDRUP M., HOFFMANN L., GYLDENKÆRNE S., MIKKELSEN M., ALBREKTSEN R., LYCK E., THOMSEN M., HJELGAARD K., NIELSEN O.-K. 2011. Monte Carlo (Tier 2) uncertainty analysis of Danish greenhouse gas emission inventory, Greenhouse Gas Measurement and Management 1(3-4) 145–160. doi:10.1080/20430779.2011.621949.

FPS. 2019. How smog affects children's brains, Foundation for Polish Science. https://www.fnp.org.pl/en/jak-smog-wplywa-na-mozgi-dzieci/.

GIG. 2016. Opracowanie bazy danych zawartości rtęci w krajowych węglach, wytycznych technologicznych jej dalszej redukcji wraz ze zdefiniowaniem benchmarków dla krajowych wskaźników emisji rtęci — akronim Baza Hg, project No. PBS2/A2/14/2013a, The National Centre for Research and Development, [in Polish].

GUS (Statistics Poland). 2016. Consumption of fuels and energy carriers (2016). https://stat.gov.pl/obszary-tematyczne/srodowisko-energia/ energia/zuzycie-paliw-i-nosnikow-energii-w-2015-roku,6,10.html.

GUS (Statistics Poland). 2017. Energy. http://stat.gov.pl/obszary-tematyczne/srodowisko-energia/energia/energia-2017-folder,1,5.html.

GUS (Statistics Poland). 2019a. Production of industrial products in 2018. https://stat.gov.pl/en/topics/industry-construction-fixed-assets/industry/production-of-industrial-products-in-2018,9,2.html.

GUS (Statistics Poland). 2019b. Consumption of fuels and energy carriers in 2018. https://stat.gov.pl/en/topics/

environment-energy/energy/consumption-of-fuels-and-energy-carriers-in-2018,8,13.html.
HUANG Y., SHEN H., CHEN H., WANG R., ZHANG Y., SU S., CHEN Y., LIN N., ZHUO S., ZHONG, Q. WANG X., LIU J., LI B., LIU W., TAO S. 2014. quantification of global primary emissions of PM2.5, PM10, and TSP from combustion and industrial process sources, Environmental Science & Technology 48 13834–13843. doi:10.1021/es503696k.
IPCC. 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories, https://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html.
JUDA-REZLER K., REIZER M., MACIEJEWSKA K., BŁASZCZAK B., KLEJNOWSKI K. 2020. Characterization of atmospheric $PM_{2.5}$ sources at a Central European urban background site, Science of The Total Environment 713 53–65. doi:10.1016/j.scitotenv.2020.136729.
KLIMONT Z., KUPIAINEN K., HEYES C., PUROHIT P., COFALA J., RAFAJ P., BORKEN-KLEEFELD J., SCHÖPP W. 2017. Global anthropogenic emissions of particulate matter including black carbon, Atmospheric Chemistry and Physics 17 8681–8723. doi:10. 5194/acp-17-8681-2017.
KUBICA R., DĘBSKI B. 2016. The emission factors for total suspended particles and particulated matter subfractions produced during solid fuel combustion in residential and commercial sectors in Poland 2000-2013, Przemysł Chemiczny 95(3) 464–471. doi:10.15199/62.2016.3.26.
KUBICA K., KUBICA R. 2014. The estimation of the emission factors for TSP, PM10, and PM2.5 from solid fuels' combustion in the residential and services sectors for 2000-2013, [in Polish, unpublished].
LEE M., LEE J., LEE J., KIM Y., PARK Y., LEE K. 2017. Uncertainty analysis of a GHG emission model output using the block bootstrap and Monte Carlo simulation, Sustainability 9 (2017) 1–12. doi:10.3390/su9091522.
LORENZ U. 1999. Metoda oceny wartości węgla kamiennego energetycznego uwzględniająca skutki jego spalania dla środowiska przyrodniczego. (The method of the hard coal assessing taking into account the impact of its combustion on the natural environment) Studia, Rozprawy, Monografie nr 64. Wyd. IGSMiE PAN, Kraków, 84 s., [in Polish].
MCAE. 2023. Poland's Informative Inventory Report 2023. Submission under the UNECE CLRTAP and NEC Directive. Air pollutant emissions in Poland 1990–2021. https://www.ceip.at/status-of-reporting-and-review-results/2023-submissions.
MSA (Ministry of State Assets). 2019. National Energy and Climate Plan for the years 2021-2030, [in Polish]. https://www.gov.pl/web/klimat/national-energy-and-climate-plan-for-the-years-2021-2030
NCEM. 2020. Poland's Informative Inventory Report 2020. Submission under the UN ECE Convention on Long-range Transboundary Air Pollution and Directive (EU) 2016/2284. Air pollutant emissions in Poland 1990–2018. https://www.ceip.at/status-of-reporting-and-review-results/2020-submissions.
NFZ. 2018. Analiza przyczyn wzrostu liczby zgonów w Polsce w 2017 roku, [in Polish]. https://www.nfz.gov.pl/download/gfx/nfz/pl/defaultstronaopisowa/349/41/1/raport_-_zgony_w_2017_roku.pdf.
SHEN G. 2014. Emission Factors of Carbonaceous Particulate Matter and Polycyclic Aromatic Hydrocarbons from Residential Solid Fuel Combustions, Springer. doi:10.1007/978-3-642-39762-2.
SHEN G. 2015. Quantification of emission reduction potentials of primary air pollutants from residential solid fuel combustion by adopting cleaner fuels in China, Journal of Environmental Sciences 37 1–7. doi:10.1016/j.jes.2015.04.018.
QUOC BANG H., HOANG NGOC KHUE V. 2019. Air Emission Inventory, Ch. 1. doi: 10.5772/intechopen.79928.
R CORE TEAM. 2020. R: A language and environment for statistical computing, R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/.
RADOVIĆ U. 1997. Zanieczyszczenie atmosfery. Źródła oraz metodyka szacowania wielkości emisji zanieczyszczeń. Wyd. Centrum Informatyki Energetyki, Warszawa, 162 s., [in Polish].
REIZER M., JUDA-REZLER K. 2016. Explaining the high PM_{10} concentrations observed in Polish urban areas, Air Quality, Atmosphere & Health 9 517–531. doi:10. 1007/s11869-015-0358-z.
ROGULA-KOZŁOWSKA W., KOZIELSKA B., KLEJNOWSKI K., SZOPA S. 2013. Hazardous compounds in urban PM in the central part of Upper Silesia (Poland) in winter, Archives of Environmental Protection 39 53–65. doi:10.2478/aep-2013-0002.
STALA-SZLUGAJ K. 2011. Hard coal combustion in the municipal and housing sector — influence on 'low emission', Annual Set Environment Protection 13 1877–1889, [abstract in English]. http://ros.edu.pl/images/roczniki/archive/pp_2011_122.pdf.
STALA-SZLUGAJ K. 2017. Assessment of prospects for the demand of coal for the municipal and household sector in Poland, Mineral and Energy Economy Research Institute of the Polish Academy of Sciences, 2017, [in Polish, with English abstract].
TIAN J., NI H., HAN Y., SHEN Z., WANG Q., LONG X., ZHANG Y., CAO J. 2018. Primary PM2.5 and trace gas emissions from residential coal combustion: assessing semicoke briquette for emission reduction in the Beijing-Tianjin-Hebei region, China, Atmospheric Environment 191 378–386. doi:10.1016/j.atmosenv.2018.07.031.
US EPA. 2019. Report on the Environment. Particulate Matter Emissions.
WIERZCHOWSKI K., PYKA I. 2015. The initial results of the "Baza Hg" project concerning mercury in commercial products of Polish hard coal mines, Journal of the Polish 305 Mineral Engineering Society 1(16) 213–220. http://yadda.icm.edu.pl/yadda/element/bwmeta1.element.baztechd5410cc2-a830-4a41-b478-630671669a49.
WINIWARTER W., RYPDAL K. 2001. Assessing the uncertainty associated with national greenhouse gas emission

inventories: a case study for Austria, Atmospheric Environment 35(32) 5425–5440. doi:10.1016/S1352-2310(01)00171-6.

WORLD BANK. 2020. Fossil fuel energy consumption. https://data.worldbank.org/indicator/eg.use.comm.fo.zs?end=2015&start=1960.

ZHAO Y., NIELSEN C.P., LEI Y., MCELROY M.B., HAO J. 2011. Quantifying the uncertainties of a bottom-up emission inventory of anthropogenic atmospheric pollutants in China, Atmospheric Chemistry and Physics 11(5) 2295–2308. doi:10.5194/acp11-2295-2011.

ZIELIŃSKI E., WIELGUS A., DRELISZAK J., ZUKOW W. 2018. Air pollution — selected health effects in Poland, Journal of Education, Health and Sport 8(12) 641–648. doi:10.5281/zenodo.2527086.