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The impact of measures aimed at reducing low-stack emission in Poland and on energy efficiency and the household emission of pollutants

ABSTRACT: According to the European Environment Agency (EEA 2018), air quality in Poland is one of the worst in Europe. There are several sources of air pollution, but the condition of the air in Poland is primarily the result of the so-called low-stack emissions from the household sector. The main reason for the emission of pollutants is the combustion of low-quality fuels (mainly low-quality coal) and waste, and the use of obsolete heating boilers with low efficiency and without appropriate filters. The aim of the study was to evaluate the impact of measures aimed at reducing low-stack emissions from the household sector (boiler replacement, change of fuel type, and thermal insulation of buildings), resulting from environmental regulations, on the improvement of energy efficiency and the emission of pollutants from the household sector in Poland.

Stochastic energy and mass balance models for a hypothetical household, which were used to assess the impact of remedial actions on the energy efficiency and emission of pollutants, have been developed. The annual energy consumption and emissions of pollutants were estimated for hypothetical households before and after the implementation of a given remedial action. The calculations, using

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the Monte Carlo simulation, were carried out for several thousand hypothetical households, for which the values of the technical parameters (type of residential building, residential building area, unitary energy demand for heating, type of heat source) were randomly drawn from probability distributions developed on the basis of the analysis of the domestic structure of households. The model takes the coefficients of correlation between the explanatory variables in the model into account. The obtained results were multiplied so that the number of hypothetical households was equal to 14.1 million, i.e. the real number of households in Poland.

The obtained results allowed for identifying the potential for reducing the emission of pollutants such as carbon dioxide, carbon monoxide, dust, and nitrogen oxides, and improving the energy efficiency as a result of the proposed and implemented measures, aimed at reducing low-stack emission, resulting from the policy.

The potential for emissions of gaseous pollutants is 94% for CO, 49% for NO_x, 90% for dust, and 87% for SO_2. The potential for improving the energy efficiency in households is around 42%.

Introduction

According to the European Environment Agency (EEA 2018), the air quality in Poland is one of the worst in Europe. There are several sources of air pollution, but the condition of the air in Poland is primarily the result of the so-called low-stack emissions from the household sector. 88% of air pollution, mainly dust pollutants, is generated by households (ME 2015). Other sources of pollution include: transport, industry, power generation using solid fuels, and agriculture. Low-stack emissions are a source of air pollutants, such as, among others: dust, carbon oxides, sulphur dioxide, nitrogen oxides and benzo(a)pyrene. The main reason for the emission of these pollutants in Poland is the combustion of low-quality fuels (mainly low-quality coal) and waste, and the use of obsolete heating boilers with low efficiency and without appropriate filters.

To make it possible to live in a healthy environment and breathe clean air, national, regional, and local authorities make efforts in order to control and improve the air quality. The replacement of old, low-efficiency heating systems could be one of the most important and effective measures. This action has a significant ecological effect and is of high economic efficiency (WB 2018). Other important corrective actions include: changing the type of fuel used for the production of heat and hot tap water into low-carbon fuel and the energy efficiency improvement of buildings through thermal insulation. Energy efficiency is one of the main assumptions of the Europe 2020 strategy aimed at reducing the primary energy consumption by 20% in 2020 compared to the 1990 level. Due to the fact that the energy-related emissions account for almost 80% of total greenhouse gas emissions, efficient energy use can significantly contribute to environmental improvements. In Poland, approximately 34% of the total energy is used for household needs, of which 80% is used for heating purposes (Zawada and Starostka-Patyk 2016).

The authors of the article decided to assess the measurable effect, that is the reduction of pollutant emissions to the atmosphere, of the proposed corrective actions. Therefore, the aim of the study was to evaluate the impact of measures aimed at reducing low-stack emissions from the household sector (boiler replacement, change of fuel type, and thermal insulation of buildings), resulting from environmental regulations, on the improvement of energy efficiency and the emission of pollutants from the household sector in Poland. This is the first study to use stochastic modeling to assess the potential for reducing the emissions of pollutants and improving the energy efficiency in the household sector in Poland. The following pollutants were analyzed: dust, carbon monoxide, sulphur dioxide, and nitrogen oxides.

This analysis is justified in the context of the Regional Operational Programs of Poland's Provinces in the household area supported by national and EU funds, which adopted measures aimed at improving the energy efficiency and air quality through air quality through thermal efficiency improvement and co-financing the replacement of old coal-fired boilers with environmentally-friendly heating sources. Funds for these purposes should be spent rationally. Up to now, most of these funds were used to implement projects aimed at replacing coal-fired boilers/furnaces with low-carbon heat sources, including: gas boilers, district heating, or eco-pea coal or biomass boilers (Mirowski and Orzechowska 2015). The analysis carried out allowed for the verification as to whether this course of action is optimal in the context of improving the air quality and energy efficiency.

1. The model, input data, and calculations

For the purpose of the analysis, stochastic energy and mass balance models for a hypothetical household, which were used to assess the potential to improve the energy efficiency and reduce the emission of pollutants as a result of corrective actions, have been developed. The annual energy consumption and emission of pollutants were estimated for hypothetical households before and after the implementation of a given corrective measure. The three possible corrective actions to be implemented in the household sector and consistent with policies and regulations were listed. They include (Sadlok et al. 2014):

1. Replacing coal-fired individual boilers with other heat sources such as: district heating, biomass boilers, or gas boilers.

2. Replacing manually operated coal-fired boilers with class 5 (or more environmentally friendly) eco-pea fired boilers with automatic feeder.

3. Thermal efficiency improvement of buildings, including: thermal insulation of external partitions, replacement of doors and windows, and upgrading ventilation and air-conditioning systems, which will result in the maximum heat demand of 150 kWh/m^2 per year (SZOOP 2017).

Regulations related to environmental protection are another important element affecting the use of coal in households. One of the legal acts that may contribute to reducing the use of coal in households is the so-called Anti-Smog Act. It was introduced in 2015 by amending the Environmental Protection Law (EPL 2001). According to the Act, the decision to limit or prohibit the combustion of certain solid fuels depends on the resolution of the Provincial Assembly. Another legislative act that will affect the use of coal in households is the Regulation of the Minister of Development on the requirements for solid fuel boilers with a capacity of maximum 500 kW (MEDF 2017). Solid fuel boilers meeting the emission limit values are specified in the Regulation. This regulation will come into force on January 1, 2018.

The calculations, using the Monte Carlo simulation, were carried out for 14 thousand hypothetical households, for which the values of the technical parameters were randomly drawn from probability distributions developed on the basis of the analysis of the domestic structure of households. The following technical parameters characterizing a household were adopted in the analysis:

✦ The type of residential building (single family house, apartment in a multi-family building);
✦ Year of the building's construction;
✦ The unit demand for heating energy expressed in kilowatt hours per square meter per year;
✦ Dwelling area in square meters;
✦ Heat source type (district heating from coal-fired heating plant or combined heat and power plant, natural gas fired boiler, manually operated coal-fired boiler, class 5 (or more environmentally friendly) automatically operated coal-fired boiler, heating oil-fired boiler, biomass (pellet) fired boiler, or electric furnace).

Statistical data of the Central Statistical Office indicate that the share of multi-family buildings in the total number of households in Poland amounts to 55.3%. Meanwhile, the share of detached, semi-detached, and terraced houses amounted to 44.7% (CSO 2016).

Table 1 shows the age structure of residential buildings in Poland. The largest share is attributed to houses built after the Second World War up until the year 1970. A small share of just over 9% is attributed to the oldest buildings, built before 1918. New residential buildings, meaning those built after the year 2002, have the lowest share. The age of a residential building is strongly correlated with its area and individual heat demand. The analysis carried out has shown that the later the residential building was built, the larger the average area of residential units. The correlation coefficient determined on the basis of statistical data for the age of the building (and hence the unit energy demand) and the average surface area of the premises is 0.75. Table 1 presents the primary energy demand for household heating. The demand increases with the age of the building. This is due to changes in energy standards in the household sector. At the same time over 92% of the buildings have a medium, low or very low energy standard.

Table 2 shows the structure of residential space in Poland. It is dominated by residential premises with an area of 40 to 80 m^2, which account for 52.3% of all residential units. Residential units in single-family homes are larger than those in multi-family buildings, on average by about 26% (Local Data Bank of Central Statistical Office).

TABLE 1. The age structure of residential buildings and the unit demand for primary energy

TABELA 1. Struktura wiekowa budynków mieszkalnych i jednostkowe zapotrzebowanie na energię pierwotną

No.	Year of construction	Percentage share	Minimum heat demand [kWh/(m²*year)]	Maximum heat demand [kWh/(m²*year)]
1	before 1918	9.01	350	500
2	1918–1944	11.46	300	350
3	1945–1970	27.62	250	300
4	1971–1978	16.08	210	250
5	1979–1988	16.38	160	210
6	1989–2002	11.31	140	180
7	2003–now	8.14	100	150

Source: (CM 2015, CSO 2011).

TABLE 2. The structure of residential space

TABELA 2. Struktura powierzchni lokali mieszkalnych

No.	The area of residential premises [m²]	Percentage share
1	below 30	4.3
2	30–40	12.2
3	40–50	18.1
4	50–60	15.3
5	60–80	18.9
6	80–100	8.9
7	100–120	7.7
8	120–200	9.5
9	over 200	2.8

Source: (CSO 2011).

Table 3 shows the structure of heat sources in households broken down by building type and the emission of pollutants (SO_2, NO_x, dust, and CO), depending on the type of heat source.

Based on the data presented above, the probability density distributions of the individual parameters were prepared, which were used in the simulation model. A total of 5 probability density distributions for the following parameters: the type of residential building, residential building area, unit energy demand for heating, and the type of heat source in single-family houses and households were developed. These distributions were developed on the basis of statistical data characterizing the household sector in Poland. The probability distributions for these parameters are presented below.

TABLE 3. The structure of heat sources in residential buildings and emission levels

TABELA 3. Struktura źródeł ciepła w lokalach mieszkalnych oraz wielkość emisji

No.	Heat source type	Percentage share		Emissions [g/kWh]			
		single family houses	households	SO$_2$	NO$_x$	dust	CO
1	District heating (coal-fired heating plants)	1	53	0.3381	0.1950	0.0216	0.0833
2	Natural gas-fired boilers	37	32	0.0018	0.2520	0.0018	0.1080
3	Heating oil-fired boilers	3	2	0.5040	0.2520	0.0180	0.1440
4	Manually operated coal-fired boilers (excluding class 5 boilers)	28	6	3.2401	0.4680	1.4400	14.4004
5	Automatically operated coal-fired boilers (at least class 5 boilers)	7	2	1.6200	0.7200	0.2880	1.4400
6	Solid biomass-fired boilers	20	1	0.0720	0.5400	0.2520	1.0800
7	Electrically powered furnaces	4	4	0.9017	0.5200	0.0575	0.2222

Source: (BDP 2012; Kubica et al. 2004).

During the simulation, random values characterizing a hypothetical residential building are based on the probability density distributions for the unit energy demand for heating and residential building area. It was assumed that both distributions were correlated and the Pearson's correlation coefficient was 0.75. The product of both values is the value of the annual demand for heating for the premises (kWh per year). The types of heat source were randomized based on the probability distribution of heat sources used in residential buildings. Different probability distributions of the heat source were adopted for single-family houses and dwellings. The type of heat source used determines the amount of emission of individual pollutants (Tab. 3). Knowing the energy demand for residential heating, it is possible to estimate the emissions of individual pollutants generated by a hypothetical household/dwelling. In the next iteration, the process is repeated in the same way, generating emission values for pollutants and heating energy demand for other hypothetical households. As part of the simulation, 14,000 iterations have been performed. The obtained results were multiplied so that the number of hypothetical households was equal to 14.1 million, i.e. the real number of households in Poland. The obtained emission values were summed according to the pollutant category, which allowed obtaining the annual emissions of individual pollutants by households in Poland.

Simulations were performed for five scenarios.

The STATUS QUO scenario – presents the current emissions of pollutants and heating energy demand in the household sector in Poland.

The NO COAL scenario – presents a hypothetical situation after the implementation of actions aimed at replacing coal-fired individual boilers instead of coal-fired heat sources with other heat sources such as: district heating, biomass boilers, or gas boilers.
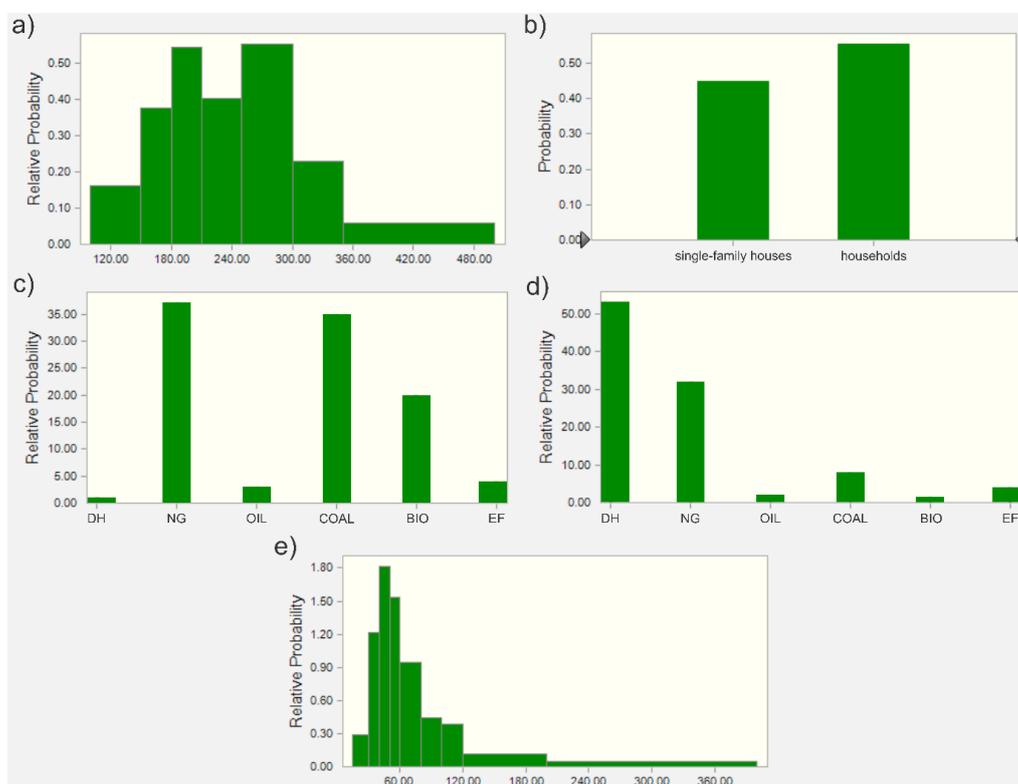
Fig. 1. The probability density distributions for the following parameters:
a) residential building area [m^2]; b) the type of residential building; c) the type of heat source in single-family houses;
d) the type of heat source in households; e) unit energy demand for heating [kWh/m^2/rok]; DH – district heating;
NG – natural gas-fired boilers; OIL – oil-fired boilers; COAL – coal-fired boilers; BIO – solid biomass-fired boilers;
EF – electrically powered furnaces
Source: own study

Rys. 1. Rozkłady gęstości prawdopodobieństwa wartości parametrów:
a) powierzchnia lokalu mieszkalnego [m^2]; b) rodzaj budynku mieszkalnego; c) rodzaj źródła ciepła w domach
jednorodzinnych; d) rodzaj źródła ciepła w mieszkaniach; e) jednostkowe zapotrzebowanie na energię do ogrzewania
[kWh/m^2/rok]

The LOW-CARBON scenario – presents a hypothetical situation after the development and implementation of actions aimed at replacing manually operated coal-fired boilers with class 5 eco-pea fired boilers with automatic feeder.

The THERMO scenario – presents a hypothetical situation after the development and implementation of actions aimed at the thermal efficiency improvement of buildings, including: thermal insulation of external partitions, replacement of doors and windows, and upgrading ventilation and air-conditioning systems, which will result in the maximum heat demand of 150 kWh/m^2 per year.

The MINI scenario – presents a hypothetical situation after the development and implementation of tow actions aimed at the thermal efficiency improvement of buildings, including: thermal insulation of external partitions, replacement of doors and windows, and upgrading ventilation and air-conditioning systems, which will result in the maximum heat demand of 150 kWh/m^2 per year and replacing coal-fired boilers with other heat sources such as: district heating, biomass boilers, or gas boilers.

2. Research and results

The simulations for each of the analyzed scenarios allowed emission values for individual pollutants and the energy demand for space heating in the domestic household sector to be determined (Table 4). The values obtained for the STATUS QUO scenario are close to those officially reported for the household sector, which confirms that the input data, assumptions, and model design are correct.

TABLE 4. Emissions of pollutants and the heating energy demand in the household sector in Poland

TABELA 4. Wielkość emisji zanieczyszczeń oraz zapotrzebowanie na energie do ogrzewania w sektorze gospodarstw domowych

No.	Scenario name	Emission of pollutants [Mg/year]				Heat demand [MWh/year]
		CO	NO$_x$	dust	SO$_2$	
1	STATUS QUO	573 190.44	71 824.72	62 162.43	163 071.14	230 035 734.66
2	NO COAL	56 788.79	62 951.23	10 963.71	34 858.37	230 035 734.66
3	LOW-CARBON	104 649.32	80 955.15	20 501.80	103 361.45	230 035 734.66
4	TERMO	338 452.66	42 133.80	36 656.85	95 390.53	134 587 965.85
5	MINI	33 358.79	36 857.71	6 469.76	20 711.17	134 498 541.93

Source: own study.

Table 5 shows the impact (expressed in percentage) of individual actions implemented under the examined scenarios on emissions and the energy demand in relation to the STATUS QUO scenario.

The obtained results show that the most environmentally friendly solution is the implementation of corrective actions according to the MINI scenario, but this is the most expensive solution, since thermal efficiency improvement is costly and has a relatively limited environmental impact, as confirmed by the emissions for the THERMO scenario. Compared to other analyzed actions, thermal efficiency improvement is best suited for NO$_x$ emission reduction. Based on the

TABLE 5. The percentage change in pollutant emissions and the energy demand for heating in relation to the STATUS QUO scenario

TABELA 5. Procentowa zmiana emisji zanieczyszczeń i zapotrzebowania na energię do ogrzewania w stosunku do scenariusza STATUS QUO

No.	Nazwa scenariusza	Emission of pollutants				Heat demand
		CO	NO_x	dust	SO_2	
1	NO COAL	–90%	–12%	–82%	–79%	0%
2	LOW-CARBON	–82%	+13%	–67%	–37%	0%
3	TERMO	–41%	–41%	–41%	–42%	–42%
4	MINI	–94%	–49%	–90%	–87%	–42%

Source: own study.

obtained results, it can be concluded that moving away from coal as a fuel for the production of heat in individual boilers (the NO COAL scenario) will result in a significant reduction of pollutant emissions and thus a very effective corrective action against low-stack emissions. However, Poland is a country with a relatively not wealthy society, so moving away from coal and switching to alternative fuels such as: natural gas, heating oil, or biomass, which are more expensive, will contribute to economic problems in the household sector. Therefore, replacing manually operated coal-fired boilers with class 5 eco-pea fired boilers with automatic feeder seems more favorable. Coal is a relatively inexpensive fuel, so a large part of the community, which has previously used this fuel for space heating, does not want to move away from this energy carrier. Therefore, replacing boilers seems to be more likely to be accepted by the society; at the same time, this solution has a significant ecological effect, reducing the emission of pollutants by 82% (CO), 67% (dust), and 37% (SO_2). The increase in NO_x emissions results from a higher combustion temperature due to the use of combustion air blowers in boilers with automatic feeder. NO_x emissions can be significantly reduced by using boilers meeting the requirements of the Ecodesign Directive.

Summary

The obtained results allowed for the identification of potential for reducing the emission of pollutants such as: carbon dioxide, carbon monoxide, dust, and nitrogen oxides, and improving the energy efficiency as a result of the proposed and implemented measures, aimed at reducing low-stack emissions. The complete thermal efficiency improvement (with the replacement of the heat source, the MINI scenario) offers the greatest potential in reducing the emission of gaseous pollu-

tants in the household sector and is up to 94% for CO, 49% for NO$_x$, 90% for dust, and 87% for SO$_2$. Meanwhile, the potential for improving the energy efficiency in households is around 42%.

Due to the high costs of buildings' insulation, the best way to reduce emissions is to convert heat sources to low-carbon ones. This is more economically efficient than the thermal insulation of buildings and, at the same time, is more environmentally friendly as it results in a higher reduction of pollutant emissions.

Summing up the previous considerations, it can be concluded that there is a significant untapped potential for increasing the energy efficiency and reducing the emission of gaseous pollutants from the household sector in Poland. The introduced regulations, the proposed legislative changes, and the implemented programs aimed at reducing low-stack emissions will play an important role in improving the energy efficiency of households and have real effects in reducing the emission of pollutants.

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Wpływ działań zmierzających do ograniczenia niskiej emisji w Polsce na efektywność energetyczną i emisję polutantów w gospodarstwach domowych

Streszczenie

Celem pracy była ocena wpływu działań zmierzających do obniżenia niskiej emisji w gospodarstwach domowych (wymiana kotłów, zmiana rodzaju paliwa, docieplenie budynków) wynikających z regulacji prawnych w zakresie ochrony środowiska na poprawę efektywności energetycznej i emisję polutantów w sektorze gospodarstw domowych w Polsce. Zbudowano stochastyczne modele bilansu energii i masy dla hipotetycznego gospodarstwa domowego, które zostały wykorzystane do oceny efektywności energetycznej i emisji polutantów realizacji działań wynikających z prawodawstwa. Dla hipotetycznych gospodarstw domowych oszacowane zostało roczne zużycie energii i emisji polutantów przed wdrożeniem danej regulacji i po jej wdrożeniu. Wykorzystując symulację Monte Carlo obliczenia zostały przeprowadzone dla kilku tysięcy hipotetycznych gospodarstw domowych, dla których wartości parametrów technicznych (liczba osób w gospodarstwie, sposób przygotowania ciepłej wody użytkowej i ogrzewania budynku, rodzaj paliwa, wiek i klasa energetyczna budynku, powierzchnia i lokalizacja budynku) były losowane z rozkładów prawdopodobieństwa przygotowanych na podstawie analizy struktury krajowej gospodarstw domowych. Otrzymane wyniki zwielokrotniono tak, aby liczba hipotetycznych gospodarstw była równa 14,1 mln, tj. rzeczywistej liczbie gospodarstw domowych w Polsce. Otrzymane wyniki pozwoliły określić potencjał w zakresie ograniczenia emisji polutantów takich jak CO_2, CO, pyły oraz NO_x i poprawy efektywności energetycznej w wyniku proponowanych i realizowanych działań zmierzających do ograniczenia niskiej emisji wynikających z regulacji prawnych. Potencjał emisję zanieczyszczeń gazowych sięga ponad 94%, natomiast potencjał w zakresie poprawy efektywności energetycznej w gospodarstwach domowych wynosi około 42%.

SŁOWA KLUCZOWE: efektywność energetyczna, symulacja Monte Carlo, gospodarstwa domowe, niska emisja