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Unit TSP Abatement Costs of Building Modernization as a Tool of Air Quality Management: Krakow Case Study

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Abstract. The problem of air quality is an urgent, and widely discussed political issue nowadays. Reducing air emissions is an expensive element of air quality management which can be reached by set of different independent means. One of the areas where solutions for improving air quality in cities can be found is the largest energy-consuming building sector, and related heating needs. The aim of the paper is to estimate the unit Total Suspended Particulates (TSP) abatement costs of building envelope modernization and replacement of heating systems with cleaner ones for buildings in the city of Krakow (Poland). Three, typical for Krakow, types of buildings are analyzed: a single-family house, a pre-war tenement house, and a block of flats. In all the options the base scenario is a coal heated building. The analyzed building's upgrade includes different combinations of changes of heat source and insulation improvements. For each of the scenarios, the costs as well as the expected effects of unit TSP emission reduction were estimated for the whole city. This approach can support the decision making, planning and financial balancing of the most beneficial activities or estimation of the expected environmental effects.

1 Introduction

Densely populated areas such as big cities, apart from social and economic benefits of urbanization, are facing also serious environmental problems [1]. One of the greatest concerns is the state of air quality. As is often emphasized, the main causes of air pollution in the cities are processes associated with burning of fossil fuels (production and energy consumption for: heating of buildings, industrial or local transport needs). City authorities take various measures to ensure sustainable development and support a resource-efficient and more environmentally friendly economy.

The building sector (with related heating needs) is the largest energy-consuming sector in Europe [2] and space heating has the biggest share in the total energy consumption in European homes. In terms of increasing energy efficiency and reducing related emissions of building sector, measures are most often taken in the area of building insulation and replacement of a heat source. Rational decision making in this matter requires sound scientific support in estimating the costs and benefits of each considered solutions.

Several studies analyzed the issue of proportions between the various alternative ways of solving a given environmental problem (e.g. determining the optimal levels of international emission reduction [3], studying the abatement cost of carbon emissions in China [4], analyzing the reduction of the water footprint of the process of growing irrigated crops [5], assessing alternative solid waste management strategies [6], trying to introduce on-road pollution exposure (health cost) as an externality of traffic [7], studying the abatement costs of GHG emissions for ethanol and electricity derived from wood [8] or analyzing cost-efficient strategy for reducing PM 2.5 levels in the Tokyo metropolitan area [9]. To our knowledge, none of the analyzed papers touched upon the abatement cost of TSP emissions in context of different strategies for buildings envelope modernization and replacement of heating systems. This study is the starting point in the thorough analysis which should precede rational decision making in this matter.

The aim of the paper is to estimate the unit Total Suspended Particulates (TSP) abatement costs of building envelope modernization and replacement of heating systems with cleaner ones, for buildings in the city of Krakow (Poland), in order to create a tool for decision-makers. Three, typical for Krakow, types of buildings are analyzed: a single-family house, a pre-war tenement house, and a block of flats. The base option for each calculation is that the building is using coal as a heat source and the building's walls and windows need improvements. The analyzed building's upgrade includes different combinations of changes of heat source and insulation improvements. For each of the scenarios, the costs as well as the expected effects of unit TSP emission reduction were estimated for the whole city. This approach can support the decision making, planning and financial balancing of the most beneficial activities or estimation of the expected environmental effects.

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2 Current air quality in Krakow

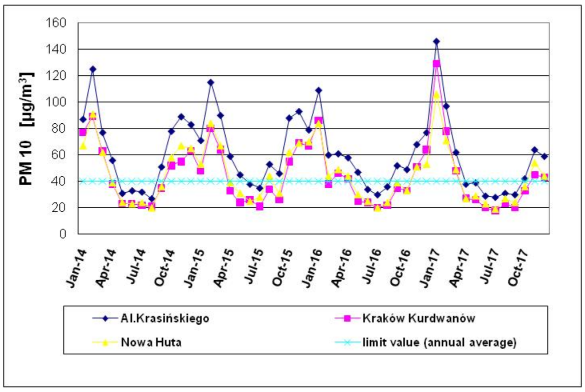
Krakow is the second largest city in Poland. It is located on the Vistula River in the northern part of the Małopolska voivodship. Krakow agglomeration covers the whole area within the administrative boundaries of the city of Krakow. Krakow has an area of 327 km^2 and is surrounded by the Krakow and Wieliczka poviats. The population of the city is at the level of 761 069 people and the density of population is 2 327 people/km^2. The city acts as an administrative, cultural, educational, scientific, economic, service and tourist center. In the eastern part of the city lies the Nowa Huta Economic Area, where are located industrial plants operating in the sector related to metallurgy (Huta Arcelor Mittal), cement industry, building and ceramics. Krakow is the second largest, after Warsaw (the capital of Poland), market for modern office space, as well as the key road and railway hub in Poland.

The city is located in the Vistula valley, at the interface of four geographical regions. From the north it borders the Krakow-Czestochowa Upland, to the south with the Wieliczka Foothills, to the west with the Oswiecim Basin, and to the east with the Sandomierz Basin. This unique geographical location of Krakow and the associated city climate with the predominance of weak western winds and frequent temperature inversions, cause poor ventilation of the city, which worsens the condition of the natural environment suffering from transport pollution, low emissions and emissions related to the industry.

The air quality in Krakow is widely recognized as extremely bad. On the one hand, it is confirmed by continuous measurements showing exceeding the acceptable standards, and on the other hand, the bad opinion about Krakow's air in comparison to other places in Małopolska region is due to the fact that there are not too many measurements of air quality outside the city. Figure 1 shows the average monthly PM10 and PM2.5 concentration in 2014-17 from three different measuring points (based on data from *Air quality monitoring system* [10]) and the permissible level of annual average concentration, according to Polish air quality standards.

Figure 1 clearly shows that the situation in the city, measured by the particulate matter (PM) concentration is very bad (especially in winter) and the problem concerns the area of entire city. The problem is similar for both types of particulate matter (PM10 and PM2.5). Sources of pollution are in the city as well as outside the city or even outside the region. The Marshal Office of the Małopolskie Voivodeship models the spread of pollution and estimates the sources [4,5]. The results are summarized in Table 1.

As can be seen from Table 1, both PM2.5 and PM10 emissions come mainly from the local sources. In case of PM2.5, the share of local sources is 76% and in the case of PM10 81%. The share of sources outside the city limits, but inside the voivodship, is 12,7% (PM2.5) and 7,8% (PM10), respectively. The largest emissions of PM10 and PM2.5 come from surface sources (mainly individual combustion from the municipal and housing sector). From outside the city limits Krakow reaches (without background) respectively 14,5% of PM2.5 and 10,5% of PM10 emissions.



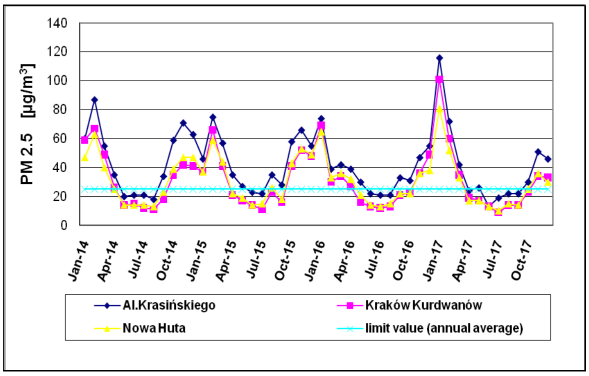


Fig. 1. The average monthly PM10 and PM2.5 concentration in 2014-17 in Krakow and the permissible level of annual average concentration (data from three different measuring points: Al. Krasińskiego, Kraków Kurdwanów, Nowa Huta).

The local sources (without background) are responsible for 28,5 µg/m^3 of PM2.5 and 49,7 µg/m^3 of PM10. With the annual average limit value of 25 µg/m^3 for PM2.5 and 40 µg/m^3 for PM10 (according to Polish air quality standards), it gives 114% of the limit value in case of PM 2.5 and respectively 124% in case of PM10.

Since the main sources of particulate matter pollutants are local sources, this problem firstly must be solved by eliminating local sources of air pollution. However, to meet the legal level of pollution, all three types of local pollution sources should be reduced. The necessity of simultaneous reduction of all sources of pollution is particularly visible with the assumption of complete liquidation of local surface sources, because at the current level of air quality flowing into the city it barely allows current standards to be met and does not guarantee compliance with the PM2.5 average annual limit value per year 2020 (20 µg/m^3).

Table 1. Sources of PM2.5 and PM10 in the air of Krakow (data reported in [11])

Sources of pollution	PM 10		PM 2.5	
	share	µg/m^3	share	µg/m^3
Background	8,2%	5,0	9,5%	3,6
Industry from outside of the voivodship	0,8%	0,5	0,6%	0,2
Transportation from outside of the voivodship	0,1%	0,1	0,1%	0,0
Surface sources (individual combustion mainly) from outside of the voivodship	1,8%	1,1	1,1%	0,4
Industry from outside of the city (other poviats)	0,0%	0,0	0,9%	0,3
Transportation from outside of the city (other poviats)	1,0%	0,6	1,5%	0,6
Surface sources (individual combustion mainly) from outside of the city (other poviats)	6,8%	4,2	10,3%	3,9
Local industry	23,7%	14,5	13,9%	5,2
Local transportation	15,1%	9,2	16,8%	6,3
Local surface sources (individual combustion mainly)	**42,5%**	**26,0**	**45,3%**	**17,0**
Total	100,0%	61,1	100,0%	37,5

The particulate matter is not the only air pollutant in Krakow. A list of main air emissions presents Table. 2

Table 2. Emission of main Krakow air pollutants (based on [11])

Area	PM 10 [Mg/yr]	PM 2.5 [Mg/yr]	SO_2 [Mg/yr]	NO_2 [Mg/yr]
Krakow	4 080	3 241	11 993	10 134

The normative level of average annual concentration of nitrogen dioxide is 40 µg/m^3 and nitrogen oxides (sum of dioxides and oxides calculated as dioxides) 30 µg/m^3. Table 3 presents the concentration of NO_2 in the Krakow air in 2015.

Table 3. Concentration of NO_2 in the air of Krakow (data from 2015 reported in [12])

Measuring points	Dominating pollutant	Annual average concentration of NO_2 [µg/m^3]
Al. Krasinskiego	road transport	63
Krakow Kurdwanow	urban background	32
Nowa Huta	industry	28

The annual average concentration of NO_2 recorded at the measuring point located at Al. Krasinskiego, which is the measuring point reflecting the influence of transportation emissions on the Krakow air, amounted to 158% of the normative value. Concentrations of NO_2 on the other two measuring points were at the level of 70-80% of the annual standard. Analysis of the variability of nitrogen dioxide concentrations in last years show a constant trend in the amount of nitrogen dioxide concentrations [12].

The areas with increased concentrations of average annual nitrogen dioxide are located along the main communication routes (A4 motorway, major transport hubs). Model studies [12] show that the main source of nitrogen dioxide responsible for its high concentration in the air in areas where the annual average is exceeded is local communication and the local industry. At these sources one should look when seeking the options for pollution reduction.

Regarding sulfur dioxide (SO_2) emissions to the Krakow air, Bokwa [13] underlines that mean annual concentrations significantly decreased comparing to the mid-1970s. Until the mid-1990s, the highest SO_2 concentrations were recorded in the city centre, where many local heating facilities operated on coal. At present, the volume of sulfur dioxide emissions shows a steady downward trend [11].

In Poland, particularly noticeable reduction of air emissions (including sulfur dioxide) took place in the 90s. This was a result of recession and economic transformation. The obsolete technologies that caused significant pollution of the environment were abandoned, changes in the energy sector were introduced (improving the efficiency of fuel used or replacing them with fuels resulting in lower emission of pollutants). New directions of the National Environmental Policy were also developed. Since then, there has also been significant progress in the installation of protective equipment (increase in number and effectiveness).

In Krakow, permissible daily mean concentrations of sulfur dioxide are exceeded in border areas with the Slaskie Voivodeship. The sources of these emissions are mostly outside the boundaries of the Małopolskie Voivodship.

Because the situation regarding air quality in Krakow is serious, and the available financial resources very limited, one should consider which activities bring the most effective environmental results and concentrate on them. The most troublesome air pollution in Krakow is particulate matter and the main source of air pollution with particulate matter are local surface sources (mainly individual combustion from the municipal and housing sector). Therefore, in the further analysis, the focus was on this aspect of the problem.

3 Calculation methodology

To estimate the effectiveness of individual methods of reducing air emissions, the amount of emissions from various sources and the costs of its reduction were estimated. In order to estimate the amount of Total Suspended Particulates (TSP) emission in a city generated from the heating of buildings, it was assumed that there are three groups of typical buildings in Krakow: single-family houses, pre-war tenement houses, and blocks of flats. For a typical building in each group, the heat demands for hot water and heating purposes were calculated. The possible emission reduction methods were adopted, either by means of modernization of the heat source or by means of wall insulation or windows' replacement. The analyzed methods of emission reduction concentrated both on the heat source and on the building envelope. In case of the heat source the replacement of a coal-fired boiler with gas or oil or connection to the municipal central heating network were analyzed. For each of these scenarios, the costs as well as the expected effects of TSP emission reduction were estimated. The additional costs of modernization have been estimated in relation to the existing condition. The running costs were calculated within the 20 years perspective. Then, the unit TSP abatement costs of each individual method were calculated and sorted in increasing order. The potential of each method for the whole city was also calculated. The number of each type of building in Krakow was estimated (based on [14]) which allowed to assess the global potential of each applied strategy.

One of the typical buildings in the city, adopted for analysis, was a single-family house. A category of a typical single-family house represents a building from the 70's/80's. It is an object with a usable area of approximately 150 m^2. The source of heat is an older type of coal boiler, working with an average seasonal efficiency of 40%. The building's unit heat demand ratio was estimated approximately as 120 [kWh/(m^2year)]. It has been assumed that outside the heating season the hot water is prepared by the electric heater, and in the heating period the water is generated by the coal boiler (which, for simplicity, is not considered in assumed unit heat demand ratio of 120 [kWh/(m^2year)], and not taken for calculation of the fuel amount or dust emissions as well).

The second category of the analyzed buildings is a tenement house. The tenement house is a typical building from the interwar period. It was assumed that it has 4 floors and 3 apartments on each floor. These apartments have an area of 37 m^2, 45 m^2 and 68 m^2. The total area of the building is 600 m^2. The building has 50 occupants, the lack of roof insulation, windows and doors of older type and natural ventilation. The heat demand index for the analyzed tenement house is approximately 200 [kWh/(m^2 year)]. It was assumed that the source of heat for these type of buildings are coal-fired boilers, and hot water is produced from flow gas heaters (as in the case of a single-family house, for simplicity, emission from hot water preparation was not considered in calculation of the fuel amount or dust emissions).

The analyzed block of flats is a typical block from a large slab. It is a building supplied with heat from the municipal central heating network, but it is equipped with a single-function heat node. The building is inhabited by 100 people. Possible emission reduction can be achieved by eliminating existing gas hot water boilers and providing hot water from the municipal central heating network. Technically that means replacing a single-function node with a multi-functional one and constructing an internal hot water installation.

The number of buildings of a given type, which can be subjected to heat source change, replacement of windows or insulation upgrade was adopted from *Observatory - portal of the Municipal Spatial Information System* [14]. 5407 single-family houses, 1033 tenement houses and 2900 blocks of flats were adopted for analysis respectively. Diagrams of possible analyzed emission reduction variants for the three typical buildings in the city are shown in Fig.2.

Table 4. Input data for various fuels accepted for analysis (based on [15,16] and building's thermal upgrade professional reports)

Fuel	Efficiency of fuel conversion (η)	Heating value (W_d)	Cost of fuel/energy $K_{p\ (gross)}$	Unit emission of Total Suspended Particulates (TSP)
Hard coal	40 %	26 MJ/kg	720 PLN/Mg	5000 g/Mg
Natural gas GZ 50	94 %	31 MJ/m^3	2,45 PLN/m^3	0,0005 g/m^3
Heating oil	90 %	42,6 MJ/kg	3,16 PLN/kg	407,18 g/Mg
District heating	100%	-	0,31 PLN/kWh	-

In order to calculate the ecological effects of individual improvements, it is necessary to adopt the value of Total Suspended Particulates emissions associated with each technology of buildings' heat supply. Table 4 presents the input data. It is assumed that the share of fly ash in coal is 5%. TSP emission factors and heating values were adopted using guidelines of the Polish Centre of Emission Balancing and Trading KOBiZE [15,16]. Efficiency of fuel conversion and current costs of fuel/energy were adopted from equipment manufacturers, fuel/energy suppliers and based on data collected from building's thermal upgrade professional reports. The improvements that have been adopted for the analysis, and consequently lead to the reduction of TSP emissions, may consist of both: reduction of the heat demand and modernization of the heat source. Modernization of the heat source may involve changing fuel, increasing efficiency of heat generation or connection to the municipal central heating network (district heating).

In the case of an external wall insulation, a 15% reduction in seasonal heat demand was assumed and in the case of a window replacement it was assumed that there would be a 10% reduction in heat demand [17]. The reduction of TSP emissions will be a consequence of the reduction in heat demand. Both, for the tenement house and for the single-family house there are 12 potential variants of TSP emissions reduction. In the case of the block of flats, the reduction of TSP emissions can only be achieved by means of one method: replacement of gas water heaters with hot water supply from the district heating network.

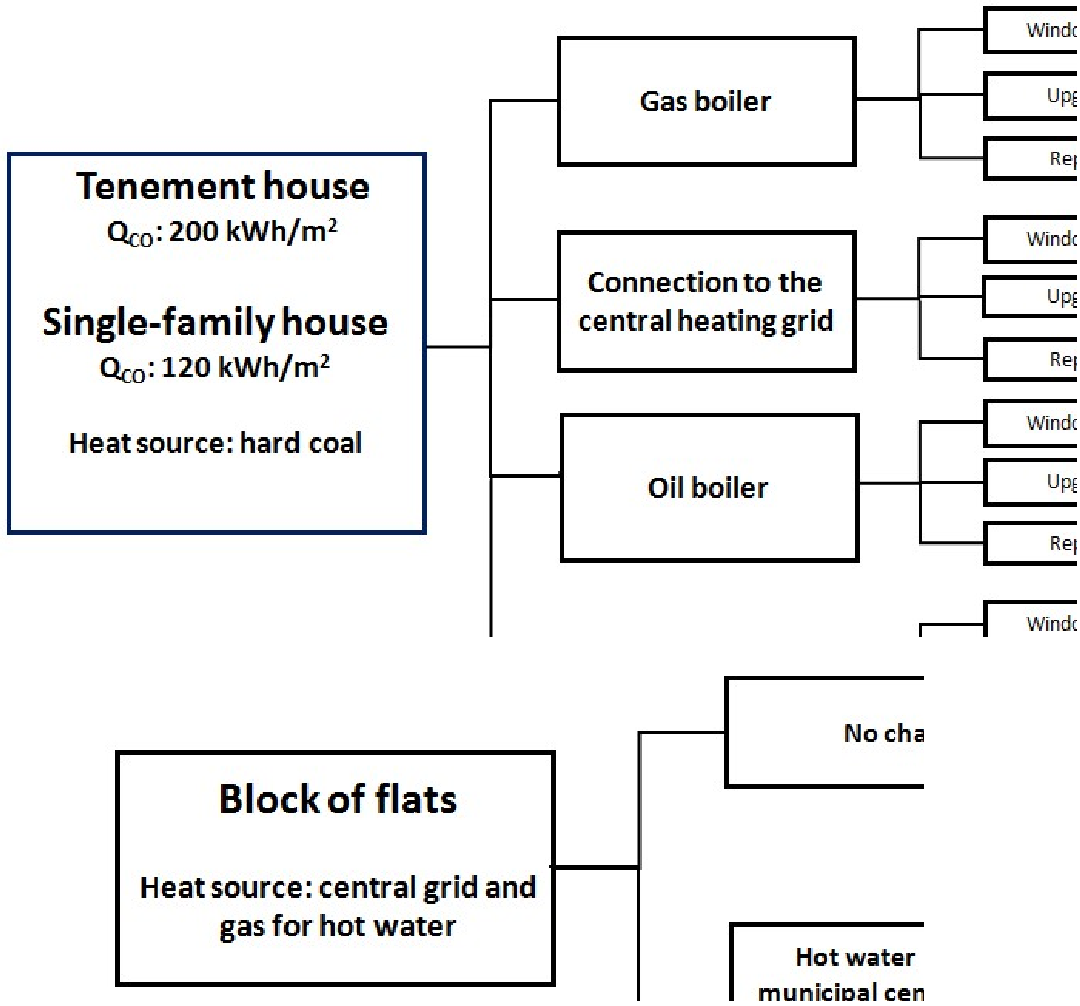


Fig.2. Analyzed variants of Total Suspended Particulates (TSP) emission reduction for the three typical buildings in Krakow.

The costs of various modernization options have been estimated based on the professional reports for building's thermal upgrade. The summary of estimated costs is presented in Table 5. The last column of Table 5 contains a more detailed description of adopted modernizations options. For example, replacement of a coal-fired boiler with a gas boiler in the single-family house (first row) is understood as replacement with the gas boiler of condensing type (working with higher efficiency than the ordinary gas boiler, and thus needs less fuel). This modernization option also includes installing a dual-function hot water tank, a hot water installation and works on chimney (due to special requirements related to the exhaust gas from gas boilers - a flue-gas duct resistant to acid).

In reality, there are more potential variants of building's improvement than presented in Table 5, because it is possible to combine work on windows with work on the walls insulation and work on the heat source. However, when calculating the economic costs and environmental effects of such complex activities, it was assumed that the final cost of all conducted works is the sum of the elementary costs, and the total environmental effect is the product of the partial effects (the effects of buildings' improvements are presented as a relative value of heat demand reduction which lead directly to reduction of calculated emissions).

For calculation of fuel costs (Table 6), only the efficiency of fuel conversion (the average seasonal efficiency of heat generation from the energy carrier) was assumed. The average seasonal efficiency of regulation and use of heat in the heating space, the average seasonal efficiency of heat transfer from the source to the heated space and the average seasonal efficiency of heat accumulation in the capacitive elements of the heating system were not taken into consideration. Fuel costs were calculated from assumed building's heat demand, fuel heating values, efficiency of fuel conversion and unit cost of fuel/energy (presented in Table 4).

Table 5. Summary of basic analyzed variants and costs of modernization (based on the professional reports for building's thermal upgrade)

No	Type of building	Type of investment	Cost of investment [PLN]	Remarks
1	single-family house	replacement of a coal boiler with a gas boiler	21 800	condensing boiler, dual-function hot water tank, hot water installation, chimney
2	single-family house	replacement of a coal boiler with oil	32 080	hot water tank, hot water installation, chimney
3	single-family house	decomissioning of the coal boiler and connection to the heating system	20 117	hot water tank, hot water installation
4	single-family house	building insulation	20 000	220 m^2 external walls
5	single-family house	replacement of windows	15 015	10 windows and balcony doors
6	single-family house	replacement of windows and insulation of walls	35 015	220 m^2 external walls and 10 windows and balcony doors
7	tenement house	replacement of a coal boiler with a gas boiler	57 327	dual-function gas boiler, hot water tank, chimney, hot water installation
8	tenement house	replacement of a coal boiler with oil	70 080	hot water tank, chimney, oil tank, hot water installation
9	tenement house	decomissioning of the coal boiler and connection to the heating system	71 120	hot water tank, hot water installation, 80m connection
10	tenement house	building insulation	110 000	1000 m^2 wall surface
11	tenement house	replacement of windows	26 157	27 windows and balcony doors
12	tenement house	replacement of windows and insulation of walls	136 157	1000 m^2 wall area i 27 windows and balcony doors
13	block of flats	decommisioning of gas water heaters and connection to central hot water	66 360	hot water tank and hot water installation

4 Unit TSP abatement costs for individual scenarios of buildings upgrade in Krakow

On the basis of the adopted assumptions of heat demand for individual buildings and input data from Table 4, the estimation of the related TSP emission and the expected TSP emission reduction can be carried out. At the same time, on the basis of the estimated costs of possible investments (Table 5) and fuel costs (Table 6), unit costs of TSP emissions reduction can be estimated using the following formula:

$$UTSPAC = \frac{IC + OC}{TSPER}$$

where:
UTSPAC – Unit Total Suspended Particulates Abatement Cost (PLN/kg),
IC – Investments Costs for each scenario (PLN) – according to Table 5,
OC – Operating Costs within 20 years, calculated as difference in fuel costs after and before modernization (PLN) – according to Table 6,
TSPER – Total Suspended Particulates Emission Reduction within 20 years (kg) – according to Table 7.

The listings of calculated unit TSP emission reductions for a given type of building, total TSP emission reductions (for the whole city) and unit TSP abatement cost (UTSPAC) in 20 years perspective for analyzed variants of building modernization are presented in Table 7.

Based on the analysis of calculated unit TSP emission reduction for a given type of a building one can say that heat source/fuel replacement, not the work on the buildings' insulation, gives significant TSP emission reductions. A primary goal of TSP emission reduction programs should be coal heated tenement houses as they have the greatest potential of TSP emission reduction at a significantly low cost. In the coal heated tenement houses the windows' replacement gives direct benefit to the investors. The efficiency of this scenario is significant, but the general potential is low. Also, in tenement houses the windows' replacement combined with changing the heat source from coal to gas is profitable. All the other analyzed methods of TSP emission reduction are not economically profitable (Table 7).

The obtained results may indicate the strategy for Krakow decision makers regarding the TSP emission reduction target in case of limited financial resources. For example, in the case of single-family houses (with a unit heat demand ratio of 120 [kWh/(m^{2}year)]) replacement of the heat source (a coal fired boiler to gas boiler) should firstly be considered. Only then should be taken into consideration windows replacement/insulation upgrade (about 30% higher unit TSP abatement cost) or linking the house to the district heating system (twice the unit TSP abatement cost in comparison to heat source changing from coal to a gas boiler).

Obtained data (Table 7) indicate that in case of single-family houses two pairs of options are equally efficient. The first one: installation of the oil boiler with no further changes or leaving a coal-fired boiler with improving insulation. The second pair of equally efficient options is: linking to the district heating system with no change of insulation/windows or installation of the oil boiler with insulation upgrade.

The variant of a single-family house with a higher value of the heat demand index was also analyzed. If the unit heat demand index is 180 [kWh/(m^{2}year)] (instead of previously assumed 120 [kWh/(m^{2}year)]), the first option for a single family house is to improve the insulation of the building. It is also the cost-effective action, which reflects the negative unit TSP abatement cost of such solution (Table 8).

The results of performed analysis show that fuel replacement gives significant TSP emission reductions. This is in tune with the government decision to ban solid fuels burning in Krakow homes. From 1 September 2019 it will be prohibited to use coal and wood in home furnaces and fireplaces (According to the adopted resolution of the Provincial Assembly [18]). From 1 July 2017 throughout the Małopolska, it is also forbidden to use mules and coal fleets. These fractions are actually coal waste - fine coal dust with grains up to 3 mm, which contains large amounts of moisture, ash and other pollutants that determine the high emission during its combustion (Anti-smog resolution of Małopolska [19]).

Table 6. Fuel costs for analyzed variants of buildings modernization

No	Building's state (building, fuel, insulation)	Fuel costs (20 yrs perspective) [PLN]
1	tenement, coal, no change	664615
2	tenement, coal, insulation improvement	564923
3	tenement, coal, windows replacement	598153
4	tenement, gas, no change	638298
5	tenement, gas, insulation improvements	542553
6	tenement, gas, windows replacement	574468
7	tenement, grid heat, no change	783158
8	tenement, grid heat, insulation improvement	665684
9	tenement, grid heat, windows replacement	704842
10	tenement, oil, no change	712217
11	tenement, oil, insulation improvement	605384
12	tenement, oil, windows replacement	640995
13	single family house, coal, no change	99692
14	single family house, coal, insulation improvement	84738
15	single family house, coal, windows replacement	89723
16	single family house, gas, no change	95745
17	single family house, gas, insulation improvement	81383
18	single family house, gas, windows replacement	86170
19	single family house, grid heat, no change	117474
20	single family house, grid heat, insulation improvement	99853
21	single family house, grid heat, windows replacement	105726
22	single family house, oil, no change	100229
23	single family house, oil, insulation improvement	85195
24	single family house, oil, windows replacement	90206
25	apartment block, no change	608657
26	apartment block, hot water from the grid	709451

Table 7. TSP emission reduction and unit TSP abatement cost for analyzed variants of buildings modernization

No	Building initial state (building, fuel)	Building's target state (building, fuel, insulation)	Unit TSP emission reduction for a given type of building (20 yrs perspective) [g/building]	Total TSP emission reduction (20 yrs perspective) [kg]	Unit TSP abatement cost (UTSPAC) (20 yrs perspective) [PLN/kg]
1	tenement, coal, no change	tenement, coal, windows replacement	415 383	429 059	- 97
2	tenement, coal, no change	tenement, gas boiler, windows replacement	4 153 703	4 290 461	- 2
3	tenement, coal, no change	tenement, gas boiler, no change	4 153 695	4 290 453	7
4	tenement, coal, no change	tenement, gas boiler, insulation improvements	4 153 723	4 290 482	11
5	tenement, coal, no change	tenement, coal, insulation improvement	623 083	643 598	17
6	tenement, coal, no change	tenement, oil boiler, windows replacement	4 071 263	4 205 307	18
7	single family house, coal, no change	single family house, gas boiler, no change	623 060	3 369 109	29
8	tenement, coal, no change	tenement, oil boiler, no change	4 062 084	4 195 826	29
9	tenement, coal, no change	tenement, oil boiler, insulation improvement	4 075 843	4 210 038	30
10	tenement, coal, no change	tenement, grid heat, windows replacement	4 153 843	4 290 606	33
11	single family house, coal, no change	single family house, gas boiler, windows replacement	623 060	3 369 109	37
12	single family house, coal, no change	single family house, gas boiler, insulation improvement	623 060	3 369 109	38
13	tenement, coal, no change	tenement, grid heat, insulation improvement	4 153 843	4 290 606	44
14	tenement, coal, no change	tenement, grid heat, no change	4 153 843	4 290 606	46
15	single family house, coal, no change	single family house, oil boiler, no change	609 320	3 294 812	54
16	single family house, coal, no change	single family house, coal, insulation improvement	93 460	505 372	54
17	single family house, coal, no change	single family house, grid heat, no change	623 080	3 369 218	61
18	single family house, coal, no change	single family house, oil boiler, insulation improvement	611 380	3 305 952	61
19	single family house, coal, no change	single family house, oil boiler, windows replacement	610 700	3 302 274	62
20	single family house, coal, no change	single family house, grid heat, insulation improvement	623 080	3 369 218	65
21	single family house, coal, no change	single family house, grid heat, windows replacement	623 080	3 369 218	66
22	single family house, coal, no change	single family house, coal, windows replacement	62 300	336 879	81
23	block of flats, grid heat, water gas heaters	block of flats, hot water from the grid	140	406	1 193 955

Table 8. TSP emission reduction and unit TSP abatement cost for analyzed variants of buildings modernization (case: single-family house with a higher unit heat demand ratio (180 [kWh / (m^2year)]))

No	Building initial state (building, fuel)	Building's target state (building, fuel, insulation)	Unit TSP emission reduction for a given type of building (20 yrs perspective) [g/building]	Total TSP emission reduction (20 yrs perspective) [kg]	Unit TSP abatement cost (UTSPAC) (20 yrs perspective) [PLN/kg]
1	tenement, coal, no change	tenement, coal, windows replacement	415 383	429 059	- 97
2	single family house, coal, no change	single family house, coal, insulation improvement	140 200	758 112	- 17
3	tenement, coal, no change	tenement, gas boiler, windows replacement	4 153 703	4 290 461	- 2
4	single family house, coal, no change	single family house, coal, windows improvement	93 460	505 372	1
5	tenement, coal, no change	tenement, gas boiler, no change	4 153 695	4 290 453	7
6	tenement, coal, no change	tenement, gas boiler, insulation improvement	4 153 723	4 290 482	11
7	single family house, coal, no change	single family house, gas, insulation improvement	934 580	5 053 610	15
8	tenement, coal, no change	tenement, coal, insulation improvement	623 083	643 598	17
9	single family house, coal, no change	single family house, gas boiler, no change	934 580	5 053 610	17
10	single family house, coal, no change	single family house, gas, windows replacement	934 580	5 053 610	18
11	tenement, coal, no change	tenement, oil, windows replacement	4 071 263	4 205 307	18
12	tenement, coal, no change	tenement, oil boiler, no change	4 062 084	4 195 826	29
13	tenement, coal, no change	tenement, oil boiler, insulation improvement	4 075 843	4 210 038	30
14	single family house, coal, no change	single family house, oil, insulation improvement	917 080	4 958 981	33
15	tenement, coal, no change	tenement, grid heat, windows replacement	4 153 843	4 290 606	33
16	single family house, coal, no change	single family house, oil, windows replacement	916 040	4 953 358	36
17	single family house, coal, no change	single family house, oil, no change	913 980	4 942 219	36
18	single family house, coal, no change	single family house, grid, insulation improvement	934 620	5 053 826	43
19	tenement, coal, no change	tenement, grid heat, insulation improvement	4 153 843	4 290 606	44
20	tenement, coal, no change	tenement, grid heat, no change	4 153 843	4 290 606	46
21	single family house, coal, no change	single family house, grid, windows replacement	934 620	5 053 826	47
22	single family house, coal, no change	single family house, grid, no change	934 620	5 053 826	50
23	block of flats, grid heat, gas water heaters	block of flats, grid hot water	140	406	1 193 955

5 Summary and conclusions

The paper estimates the unit TSP abatement cost for different options of building upgrades in the city of Krakow (Poland). Three, typical for Krakow, types of buildings were analyzed. In all the options the base scenario was that the analyzed building is heated by coal or in case of apartment block it is connected to the grid, but hot water is generated in individual gas heaters. The analyzed building's upgrade scenarios included different combinations of heat source changes as well as insulation improvements. For each analyzed scenario unit TSP abatement cost were calculated. The obtained results are general and not universal for all the buildings in the city. They cannot be used as a binding recommendation in individual cases. In each individual case a separate analysis is required to develop the best

TSP emission reduction and energy saving strategy. This analysis is a general guideline for municipal decision makers how to prioritize their actions.

The performed analysis shows that estimated unit TSP abatement cost for the city of Krakow can help to create a tool for decision-makers, enabling planning and financial balancing of the most advantageous activities and estimation of expected environmental effects.

The obtained results indicate also that:

- Very few of the analyzed strategies of TSP emissions reduction are economically sound. If the city wants quick and significant improvements of the TSP emission reduction from private houses a system of financial or administrative incentives has to be developed.
- Heat source/fuel replacement, not the work on the buildings' insulation, can give a significant TSP emission reductions.
- Coal heated tenement houses should be a primary goal of TSP emission reduction programs.
- For single-family houses with high unit heat demand ratio the insulation upgrade should be considered before the heat source change.
- Improvements on hot water supply in block of flats give very little TSP emission reduction at a very high cost.
- The application of unit TSP abatement cost to develop the municipal strategy of TSP emission reduction requires calculation of numerous other options of potential buildings improvement strategies.
- The calculations of the unit TSP abatement cost for different transportation strategies should also be considered.

The performed analysis and obtained results are a starting point to more accurate calculations and to estimate the marginal costs of TSP emission reduction for different strategies in the city of Krakow, which can serve for determination of the proportion between the various alternative ways of solving a problem of TSP emission and air quality.

Abbreviations and symbols

TSPER	- Total Suspended Particulates Emission Reduction within 20 years (kg).
IC	- Investments Costs (PLN)
OC	-Operating Costs within 20 years (PLN)
PM	- Particulate Matter
TSP	- Total Suspended Particulates
UTSPAC	- Unit Total Suspended Particulates Abatement Cost (PLN/kg),

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