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City-level energy planning aimed at emission reduction in residential sector with the use of decision support model and geodata

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Abstract. The article presents an energy-economic model that can be used for decision support in developing strategies aimed at reduction of air pollutant emissions from the residential sector. The model was developed with the use of the General Algebraic Modelling System (GAMS). It is a bottom-up model coupled with the GIS-based tool making use of the geo-referenced datasets describing buildings. These data sets include, among the others, the building boundaries, utility types, location, number of floors. At first, an energy demand for space heating was estimated at the building level. Then, the model solved the Mixed Integer Programming (MIP) problem by taking measures: (i) on the supply side (e.g. fuel and/or technology switch) and (ii) on the demand side (e.g. replacement of windows, improving insulation of the building envelope and the roof). The objective function minimized by the model was the total cost of covering heat demand. A number of user-constraints were defined, including, e.g. limitations of emissions of air pollutants, dedicated budget for emissions reduction, priority given to either demand-side or supply-side measures. The applicability of the model was demonstrated in a case-study done for a town in Poland. Several scenarios were considered to show the strategies to decrease emissions and the respective implementation costs. The results showed that emission reduction could be achieved with negative costs due to investments in thermomodernization of energy intensive buildings.

1. Introduction

Poland belongs to a group of countries with worst air quality in Europe. The main reason of such situation is the massive use of low quality coal in old and inefficient boilers for space heating in residential sector. Households are the largest final consumers of energy in Poland (the share is approx. 31%) [1]. During winter time this is leading to “low-stack emissions” of particulate matter and other hazardous substances such as mercury, which is becoming a growing concern the EU level [2]. Coal is still popular as a domestic fuel not only due to its attractive price but also due to the fact that people have used it for decades, are simply used to it and do not pay attention to other alternatives. The majority of central heating installations within existing buildings particularly in rural areas are designed for solid fuel boilers. In the last few years, however, situation has started to change. Air quality regulations supported by gradually growing awareness of citizens on the negative health impact of air pollution have increased their interest to change heating technology to a less polluting one. The Polish Government through its agencies has launched several programs supporting financially the voluntary replacement of old heating technologies. In some cities and regions the local law has been introduced to ban the use of coal for space heating e.g. Kraków [3]. There is still a huge need



for continuation of this transition process. However, the financial support for necessary investments is limited and public money should be spent in the best possible manner leading to highest improvements in air quality.

Therefore, there is a need for tools that can be used to assess the costs and benefits of possible building-based solutions leading to emission reduction. These options include, among the others, supply side measures (SSM) such as: technology- and fuel- switch as well as demand side measures (DSM) which are aimed at the reduction of heat demand (and thus final fuel consumption).

There exist tools designed for optimization of energy system development considering air pollution on the national level [4,5]. Also numerous regional and city-level energy planning models can be found [6-9]. This paper presents an energy-economic model built to support the development of strategies to reduce emission of air pollutants at the city level. This model is tailored for cities in which individual heating systems in households are the main cause of air pollution and transition to low emitting technologies is demanded with limited financial resources available. The capabilities of the model were demonstrated in the case study performed for a town named Kalwaria Zebrzydowska located 40 km south-west of Krakow/Poland. The model was seeking for cost-optimal combination of heating technology and thermomodernization options to satisfy the useful heat demand while meeting the environmental constraints. The use of a geo-referenced dataset for buildings made it possible to consider each building individually and to explore the geo-processing tools.

2. Description of the model

The model has been designed to solve the Mixed Integer Programming (MIP) problem. In each building belonging to a system (city of Kalwaria Zebrzydowska) a decision can be made regarding the following improvement options:

- Replacement of windows;
- Thermomodernization of the outer walls envelop;
- Insulation of roofs;
- Replacement/modernization of the central heating system;

2.1. Description of buildings covered by the case study

The case study was conducted for a small town with ca. 5000 citizens named Kalwaria Zebrzydowska located 40 km south-west of Krakow/Poland. The town was selected as its Monastery is a UNESCO World Heritage Site making the town tourist destination in Lesser Poland. At the same time the air quality standards seem to be often exceeded. According to the [10] residential buildings (mostly one-family buildings - OFH) have approx. 90% share in the current overall final heat consumption. Therefore, this study was focused only on OFH. In total 1090 of such buildings were taken into account. Each building has been assigned to one of the 7 age classes depending on its construction year. Local visual inspection was made by students in 2016 to physically evaluate the state of buildings' walls envelopes, windows and roofs. They filled-in a questionnaire characterizing the building components. The database was created in which the state of each building was described. There was also information to which vintage group it belongs.

2.2. Estimation of the useful heat demand of the buildings

Detailed calculation of the useful heat demand of each building would require making hundreds of energy audits. This went beyond the scope of this study, which was aimed at the development of the decision support model. In this study the basis for the specification of the useful head demand of each building was the database of the TABULA project [11]. Within this project, among the others, Polish national building typology was developed in which residential buildings were divided into several stocks based on their function (e.g. one family or multi-family) and construction period. In each stock, one representative building was indicated with its energy characteristics presented in details. The useful heat demand coefficient Q^u is the highest in case of older buildings. The newer is the building the lower heat demand (due to lower U-values of materials and building's elements, which at present are determined by the law). Additionally, heat demand also decreases if the thermal efficiency

improvement options have been applied to the building. The values of the useful heat demand coefficients used in this study can be found in [11].

2.3. Replacement of the central heating system

According to [9] nearly 90% of buildings in Kalwaria Zebrzydowska are heated with hard coal and the remaining part by natural gas. It is very common that the boilers used are oversized. If the model decided to leave the existing heating system it stayed as in the existing situation i.e. oversized. For the sake of the study it was assumed that for new boilers there were only three thermal capacity classes (c): (i) $c \leq 14$ kW, (ii) $14 \text{ kW} < c \leq 19$ kW, (iii) $c > 19$ kW (in the last case the cost parameters of the boiler of the size 25 kW were assumed). Besides natural gas and coal also oil boilers and electric heaters could replace the existing boilers. Technical and economic parameters of technologies are presented in Table 1.

Table 1. Technical and economic parameters of boilers [12].

Technology type	Fuel	Efficiency [%]	Efficiencies of transmission, regulation and accumulation process [%]	Thermal capacity c (kW)	Investment costs (PLN kW ⁻¹)	Fuel price (PLN kWh ⁻¹)
WK_1_14*	Hard coal	70	84	$c \leq 14$	0	0.13
WK_1_19	Hard coal	70	84	$14 < c \leq 19$	0	0.13
WK_1_25	Hard coal	70	84	$c > 19$	0	0.13
GAS_1_19	Natural gas	90	84	$c > 19$	0	0.25
WK_5_14	Hard coal	91	84	$c \leq 14$	744	0.16
WK_5_19	Hard coal	91	84	$14 < c \leq 19$	569	0.16
WK_5_25	Hard coal	91	84	$c > 19$	465	0.16
GAS_14	Natural gas	95	84	$c \leq 14$	300	0.25
GAS_19	Natural gas	95	84	$14 < c \leq 19$	270	0.25
GAS_25	Natural gas	95	84	$c > 19$	250	0.25
EE_14	Electricity	99	90	$c \leq 14$	331	0.38
EE_19	Electricity	99	90	$14 < c \leq 19$	382	0.38
EE_25	Electricity	99	90	$c > 19$	508	0.38
OO_14	Fuel oil	95	84	$c \leq 14$	506	0.43
OO_19	Fuel oil	95	84	$14 < c \leq 19$	423	0.43
OO_25	Fuel oil	95	84	$c > 19$	366	0.43

*WK_1** stands for old coal boiler and the ending _14 inform about the capacity i.e. 14 kW in this case.

2.4. Thermomodernization options for buildings

There are three thermomodernization options for buildings considered in the model. First of them is replacement of windows. According to [13] in rooms intended for living of people the ratio of windows area to floor area should be at least 1:8. However, not every floor in the building is used for living and to compensate for this, two windows were subtracted from the calculated number of windows per each floor. It was assumed that the old window will be replaced with a new double-leaf and double-glazed window with the size of ca. 1160 x 1400 mm. The overall replacement cost is 950 PLN. As regards to the thermo-modernisation of the outer walls envelop it was assumed that the polystyrene foam will be used, which at present is the most widely used insulating material in Poland.

The surface area of buildings was calculated with the assumption that each building is a square prism with the height of each floor equal to 3.5 m. The estimated cost of insulating 1 m² is approx. 80 PLN (including labour cost). In case of the last thermo-modernization option i.e. insulation of roof it was assumed that the area to be insulated is the area of the outer contour of the building calculated with the use of GIS processing tools. The approximate cost of this insulation considering mineral wool equalled 100 PLN/m².

3. Equations and mathematics

The model was developed with the use of the General Algebraic Modelling System (GAMS). It is a bottom-up model operating at the building level. The model was coupled with the Quantum GIS (QGIS). In this way it could be supplied with geo-referenced dataset for buildings as well as its results could be processed and visualized with the use of QGIS. Additionally, some spatially determined constraints can be defined in QGIS and implemented into the GAMS model. This chapter provides an outline of a specification of the mathematical programming problem describing the interactions of fuel/technology switch and thermal efficiency improvement options for buildings. Goal function and main constraints are presented.

3.1. Global Sets

The model definition requires the use of the following sets:

$b \in B$	= {1,2,...,1090},	buildings numbers
$o \in O$	= {1,2}	windows (1-inefficient, 2-efficient)
$s \in S$	= {1,2}	wall insulation (1-inefficient, 2-efficient)
$d \in D$	= {1,2}	roof insulation (1-inefficient, 2-efficient)
$t \in T$	= {HC, GAS,OIL,ELC}	heating technology
$p \in P$	= {PM ₁₀ , SO ₂ , BaP, CO ₂ }	pollutants
$y \in Y$	= {A,B,C,D,E,F,G}	age classes depending on the construction year

3.2. Representation of a building

The building is defined by a set with the following elements:

$$\{b,o,s,d,t,y\}$$

The first element is a subset containing building numbers. The next three stand for windows (o), walls (s) and roof (d), respectively. Subset (t) contains all heating technologies. Finally (y) informs about the vintage year of the building.

3.3. Decision variable

One of the most important decision variables is a binary variable Ψ which is used to choose the allowed combination of thermal efficiency improvements as well as a heating technology:

$$\Psi_{b,o,s,d,t,y} = \begin{cases} 0 & \text{if combination is refused} \\ 1 & \text{if combination is accepted} \end{cases}$$

To better understand the possible choices of the model let us consider a specific building (with its given number), with bad windows, inefficient walls and roof insulation. This building can be thermo-modernized by improvement of any, all or combination of its components: o,s,d. Beside thermal efficiency improvements also a new heating technology can be introduced in place of the existing one (e.g. natural gas boiler can replace the existing coal boiler). By implying certain constraints e.g. the maximum budget for investment in reduction of emissions, it is left to the model to decide which of the options mentioned above are to be chosen.

3.4. Main equations

Let's imagine that the model seeks for solution for our building. Then, certain number of thermal efficiency improvements are possible, but also heating technology switch have to be considered. Since,

$$\sum_o \sum_s \sum_d \sum_t \sum_y \Psi_{b,o,s,d,t,y} = 1 \quad (1)$$

The model can chose only one combination of options for that building.

The goal function is the total system cost:

$$\text{Cost} = \sum_{b,o,s} \sum_d \sum_t \sum_y C_{b,o,s,d,t,y} \cdot \Psi_{b,o,s,d,t,y} \quad (2)$$

and

$$C = F + I^t + I^o + I^s + I^d \quad [\text{PLN}] \quad (3)$$

where

F - fuel costs over the lifetime of 15 years,

I - investment costs into thermal efficiency improvements and change of the heating technology.

At present solid fuel fired boilers dominate in the studied area. In the normal operation conditions the steel from which such boilers and their heat exchangers are made-off is worn out mainly due to low temperature corrosion. In case of new solid-fired boilers with good control of the combustion process the projected operation life time is around 15 years. Obviously the lifetime of other heating technologies such as natural gas fired boilers or heat pumps could reach over 20 years but for simplicity and transparency of calculations one period was considered in economic analysis equal to 15 years.

To calculate emissions of air pollutants the final fuel consumption need to be known. At first the total heated area A^f of the building was calculated based on the GIS data according to the formula:

$$A_b^f = A_b^z \cdot l \cdot \text{cor}_b^f \quad [\text{m}^2] \quad (4)$$

where:

A^z - building area on the outer contour of the building [m^2],

Cor- heated area calibration ratio equal to 0.8 [8],

l - number of floors above ground level.

In order to calculate the final energy consumption from useful heat demand it was necessary to take into account the efficiency of the heating source as well as efficiencies of transmission, regulation and accumulation. The values used in this study and presented in Table 2 are based on

Then, the final energy consumption is calculated for each building using the relevant useful heat demand coefficients Q^u (see Paragraph 2.2) taking into account the overall efficiency of the heating system according to the following equations:

$$E_b = \frac{A_b^f \cdot Q_b^u}{\eta} \quad [\text{kWh} \cdot \text{yr}^{-1}] \quad (5)$$

One of 56 available values of Q^u is assigned to each building depending on its construction year and condition of its windows, walls and roof. For instance, the value of Q^u for one family building belonging to the "A" age class(meaning that it was built before 1945) for which all its components

{o,s,d} are in a bad shape is equal to $182.3 \text{ kWh}\cdot\text{m}^{-2}\cdot\text{yr}^{-1}$ whereas for modern building of the same type Q'' is equal to $64.6 \text{ kWh}\cdot\text{m}^{-2}\cdot\text{yr}^{-1}$.

Finally, emissions of air pollutants are calculated using emission factors presented in Table 2.

Table 2. Emission factors of pollutants [14].

Technology type	Particulate matter -PM ₁₀ (gGJ ⁻¹)	Benzo(a)pyrene (mgGJ ⁻¹)	Mercury (mgGJ ⁻¹)	Carbon dioxide (kgGJ ⁻¹)
Hard coal 1*	225.00	150.00	5.10	93.74
Hard coal 5	78.00	55.00	5.05	93.74
Natural gas	0.50	0.00	0.68	55.82
Fuel oil	2.00	0.08	0.12	76.59

4. Description of the analysed scenarios

In order to demonstrate the application capabilities of the model few scenarios were prepared. There were differentiated based on various types of constrains, such as, emission limits, limited budget for emission reduction expenditures, giving priority to demand-side or supply-side measures. The description of the scenarios is presented in Table 3. In this table it is also indicated if demand and supply side measures were allowed in a given scenario and what were the main constraints considered.

Table 3. Description of main scenarios considered in the study.

Name	Description	SSM	DSM	Constraints
Existing	Existing situation	No	No	Fixed heat generation in every building as in the existing situation.
Baseline	Investments in thermo-modernization and heating technology switch allowed.	Yes	Yes	No.
O-Emiss-Cap	Demonstration of how the model can be used to reach a citywide targets.	Yes	Yes	Overall emission of PM ₁₀ cut by 50% as compared to the existing situation.
A-Emiss-Cap	Demonstrate how the model can be used to reach zonal targets.	Yes	Yes	PM ₁₀ emissions cut by 80% only in the selected area. This target was set on the top of the Baseline.
DSM-Only	30% emission reduction through DSM.	No	Yes	Only thermo-modernisation options are allowed.
SSM-Only	30% emission reduction through SSM.	Yes	No	Only fuel/technology switch is allowed.
Limited budget	The available money to be spent on emission reduction was limited.	Yes	Yes	On the top of the Baseline scenario additional investments needed to be made equal to 2% of the city annual budget (ca. 1.4×10^6 PLN).

The Baseline scenario is the cost optimal scenario without any constraints. It has the lowest heat supply cost. Decrease of PM emissions is the co-benefit of this least-cost solution.

The A-Emiss-Cap scenario was prepared with the use of buffering function of QGIS. Figure 1 shows one family buildings covered by 50 m buffer that was set around 3-go Maja street (marked yellow) that have been considered in the area emission limit of the A-Emiss-Cap scenario.

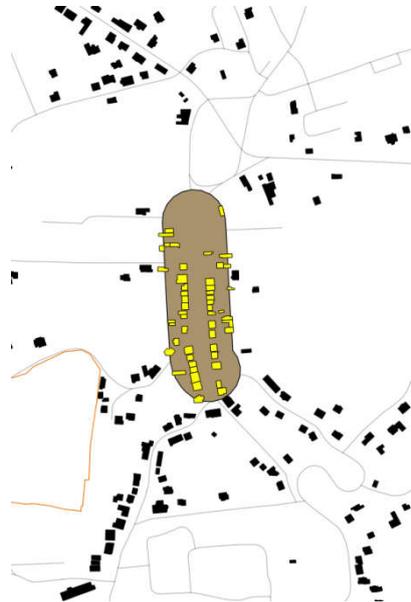


Figure 1. OFH buildings (yellow) within 50 m buffer set around 3-go Maja street.

5. Results

The quantitative results for all the scenarios are presented in Table 4.

Table 4. Results for the scenarios considered in this study.

Name	Overall costs* [10 ⁶ PLN]	Annual fuel costs [10 ⁶ PLN]	SSM Costs [10 ⁶ PLN]	DSM costs [10 ⁶ PLN]	Total PM ₁₀ emissions [t]
Existing	84.78	5.65	0.00	0.00	30.23
Baseline	80.62	4.83	1.30	7.05	28.06
O-Emiss-Cap	83.18	4.62	5.83	8.11	15.11
DSM-Only	87.72	3.97	0.00	28.14	21.15
SSM-Only	82.64	5.24	4.01	0.00	21.15
Limited-budget	80.68	4.74	1.13	8.49	27.51
A-Emiss-Cap	81.21	4.81	1.51	7.53	27.00

*Costs of technologies switch, thermomodernization measures and fuel consumption during 15 years.

It is worth noting that the Baseline scenario has lower overall costs than the Existing scenario. As a reminder, in the Baseline scenario the model has a freedom to invest in DSM and SSM options and there are no other constraints. In means that the emission reduction can be achieved at present at overall negative costs. This was possible due to investments in thermomodernization (total DSM expenditures equaled to approx. 7 million PLN) that has led in consequence to fuel savings during the period of 15 years. One should bear in mind, however, that at first citizens must spend their own money and this often constitute a serious barrier. The solution could be to partly support these investments from the municipality budget what was reflected through the Limited-budget scenario in which ca. 1.4 million PLN (additionally to the Baseline) could be spent on emission reduction. DSM-

Only scenario has the lowest annual fuel costs and highest thermomodernization costs. The reason of the latter is that initially investments into DSM are made mainly in old buildings which are in bad condition. Consequently, with relatively low investments substantial energy savings can be reached. Gradually, the low costs DSM options are diminishing as old buildings have been already thermomodernized. Hence, to achieve further emission cuts new buildings must undergo thermomodernization at increasingly higher costs and with increasingly lower energy savings. Scenarios O-Emiss-Cap and A-Emiss-Cap present two different strategies aimed at emission reduction. The former reflects the situation in which a global target is set to cut overall emissions in the city. Expenditures are then made without paying attention to where emission reductions take place. The latter reflects the situation in which zonal targets are set and emission is reduced only in selected areas. This make it possible to spend money on emission reduction in places where it is the highest e.g. because of high concentration of buildings that, moreover, are energy intensive and burn low quality fuel. In both scenarios a combination of supply- and demand-side measures was applied. Citywide PM_{10} emissions were cut by 50%with capital expenditures of almost 14 million PLN. Still, in this case the overall costs incurred during 15 years were lower than in the Existing scenario. To facilitate the evaluation of the emission reduction opportunities a marginal abatement costs curve (MACC) was prepared.

The marginal abatement costs curve for PM_{10} depicted in Figure 2 shows the costs and reduction potential for OFH in Kalwaria Zebrzydowska. The starting point for constructing this curve was the existing situation. Then, several consecutive model runs were done in which more stringent emission levels had to be met (up to 90% emission reduction in relation to the Existing scenario). For each run the resulting marginal costs (i.e. the change in total costs between the results of the previous and current run) and emissions were calculated and expressed in “reduced ton” unit. One can see, that as mentioned above more than 2 tons of PM_{10} emissions can be reduced with negative overall costs. In this case, almost 90% of capital is invested into thermomodernization of buildings. Substantial reduction potential exists with relatively low costs. About 20 tons of PM_{10} can be reduced with the marginal reduction costs not exceeding 50 PLN/t.

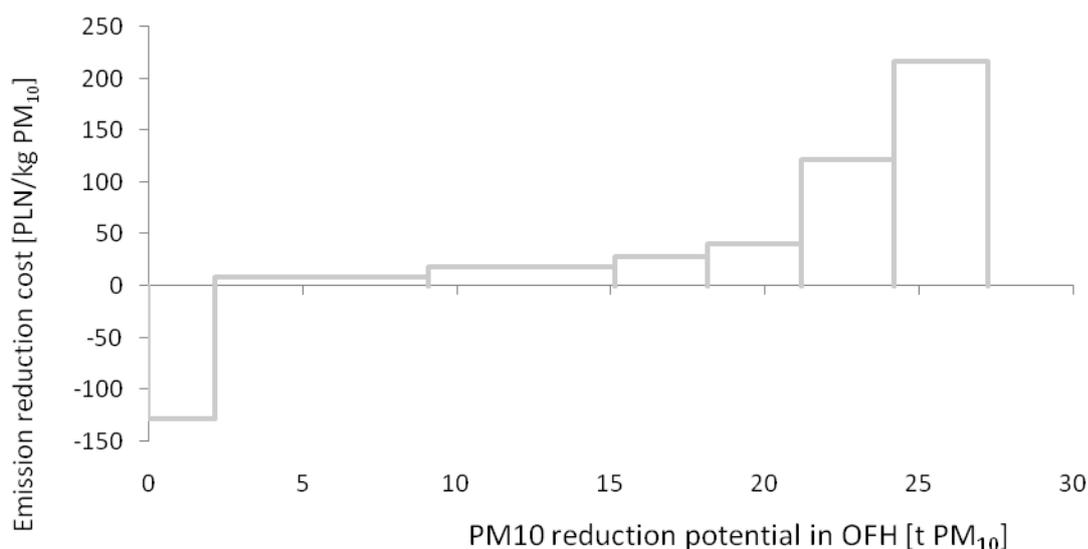


Figure 2. Marginal emission abatement costs curve for PM_{10} in Kalwaria Zebrzydowska.

The structure of investments is depicted in Figure 3. Four cases have been presented in that figure i.e. Existing situation, Baseline, 70% reduction in PM₁₀ emissions (corresponding to the marginal reduction costs of ca. 40 PLN/t PM₁₀) and 90% reduction which is the limit on the Figure 2 (the marginal reduction costs of 216 PLN/t PM₁₀).

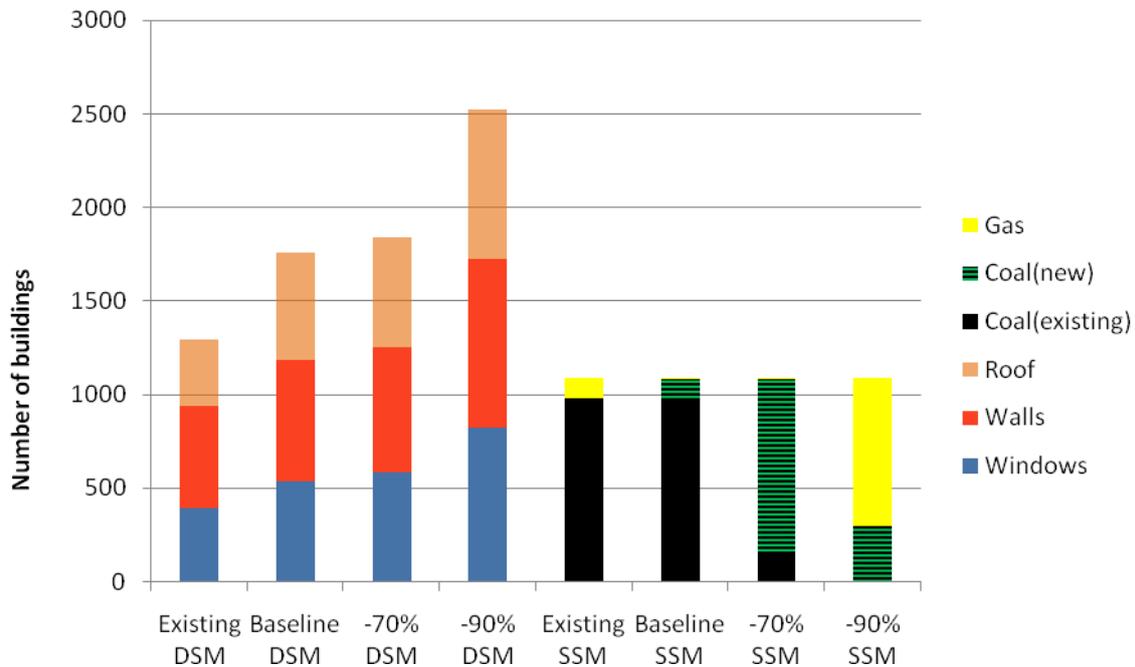


Figure 3. Number of buildings for different scenarios with certain types of investments suggested by the model i.e.: (i) with efficient widows, walls and roof (bars labelled as DSM), (ii) split into heating technologies used (bars labelled as SSM).

One can see the measures undertaken in each case on the demand side (DSM: new windows, insulation of walls and roof) as well as on the supply side (SSM: new coal and gas boilers). In the Baseline case indeed there are only small investments in new coal boilers and big investments in thermomodernization. Further reductions above the Baseline are then achieved mainly through the investments in replacement of the heating technologies. In the extreme case of 90% emission reduction majority of coal boilers is replaced with gas boilers.

The spatial distribution of PM₁₀ emissions for the Existing scenario is presented on the map in Figure 4. The calculation results are shown in the grid of spatial resolution 50m x50m covering the entire city. Such aggregation was proposed to maintain the anonymousness of residents and also to display results in clear format. The summation of buildings' emissions in the grid cells was done with the assumption that stacks are located in the center of the buildings. There are four main areas where emissions from OFH is the highest. One of them is located around 3-go Maja street, which as mentioned before was covered by a buffer for which a 80% PM₁₀ reduction target was set in the A-Emiss-Cap scenario.

The capabilities of the model to analyze possible emission reduction measures only in the selected areas (covered by a buffer) are demonstrated in Figure 5. One can compare the difference in emissions in the selected area between Existing (Fig. 4) and A-Emiss-Cap (Fig. 5) scenarios.

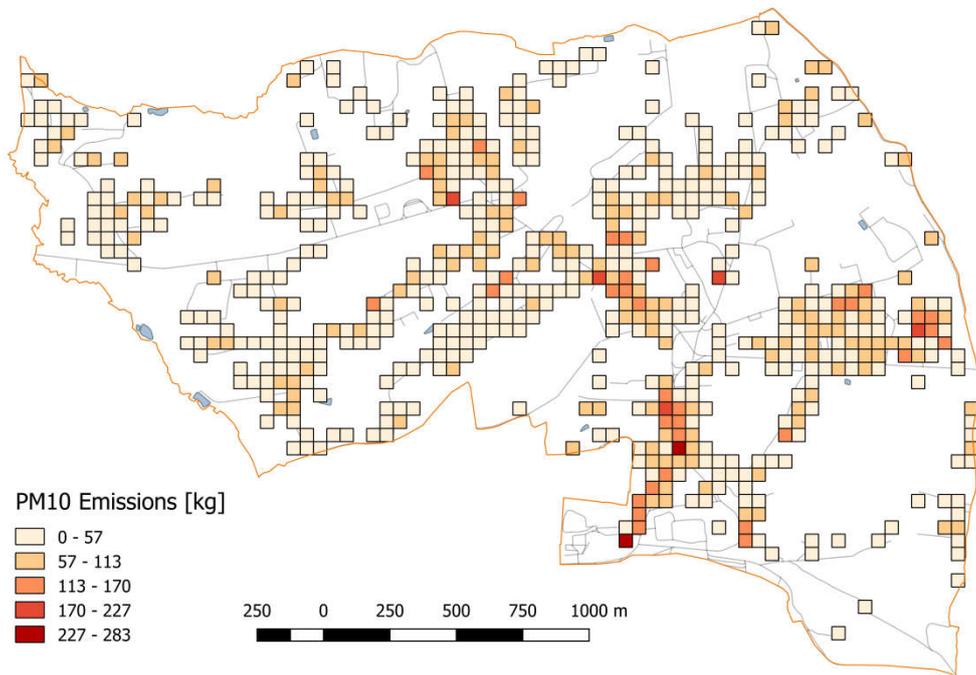


Figure 4. PM₁₀ emission map for the Existing scenario.

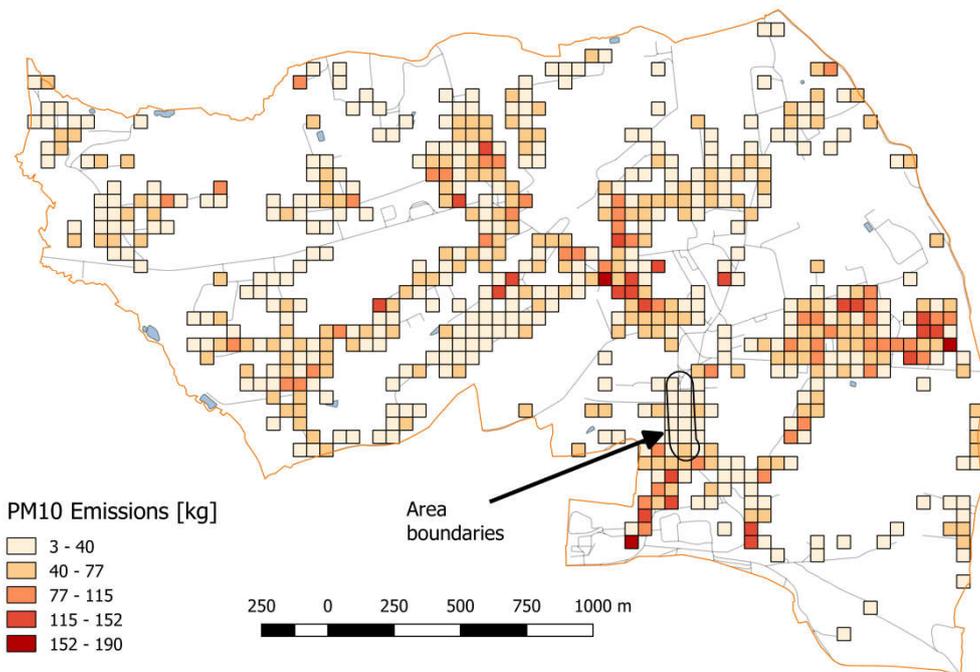


Figure 5. PM₁₀ emission map for the A-Emiss-Cap scenario.

6. Conclusions

In this paper an energy-economic model coupled with QGIS system was presented. Its aim is to support the development of strategies aimed at reduction of air pollutant emissions from the residential sector at the city level. It is a bottom-up model operating at the building level, which chooses cost optimal combination of demand- and supply-side measures to satisfy the useful heat demand. The geo-referenced datasets used included buildings boundaries, utility types, location, number of floors, heating technologies. The applicability of the model was demonstrated for the city named Kalwaria Zebrydowska located 40 km south-west of Krakow/Poland. Several emission mitigation scenarios were considered. They were differentiated based on various types of constrains, such as, emission limits, limited budget for emission reduction expenditures, priority given to demand side or supply side measures. It was shown that at present emission reduction can be reached in the city at overall negative costs. This is possible due to investments in thermomodernization, which at first takes place mainly in old buildings which are in bad shape. Consequently substantial fuel savings can be achieved at relatively low costs. Reduction of 50% in citywide PM₁₀ emissions requires capital expenditures of almost 14 million PLN. Still, in this case the overall costs incurred during duration of 15 years are lower than in the Existing scenario. It is worth mentioning that the gas price which is ca. 92% higher compared to the price of coal used in old boilers and 56% higher than coal pellets used in new boilers gas enters as the optimal solution only with very high emission constraints. However, the coal utilisation cost is slightly underestimated as it takes into account only the purchase and transport costs whereas costs of its unloading to the cellar and the cost of extra time needed for servicing coal combustion devices (loading, removal of ash, cleaning) are not taken into account. In the current version of the model it was assumed that all roofs are flat. In reality many roofs are not flat and this assumption also leads to underestimation of costs of roof insulation. The improvement in this regard may include the use of the LiDAR data to model geometry of roofs what will be the subject of the future work. The spatial distribution of PM₁₀ emissions was presented in a form of map with 50m x50m resolution covering the entire city. The approach was presented in which emission reduction target was set only for a part of the city with high emissions. Normally, also pollutants ambient concentration will be high in such areas as pollutants are emitted from low-stacks, hence, the chance for pollution dilution is limited.

The strength of the method described in this paper lies in combination of optimization model with GIS-based tool and use of geo-referenced data sets. This system can be used in any city provided that the required data are available. Further works will be devoted to enhancement of options for thermomodernization and for description of thermal state of the buildings' components. On the supply side the set of heat generation technologies will be enriched to include renewable energy sources such as biomass, which PM₁₀ emission factor when fired in modern boilers is approx. half of the one for hard coal, as well as heat pumps. A dynamic investment appraisal method that acknowledge the time value of money will be used as an alternative in the goal function.

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