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Spatial analysis of ghg emissions in eastern polish regions: energy production and residential sector

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A b s t r a c t. The characteristics of territorial distribution of greenhouse gas emission sources have been analyzed for eastern Polish regions. Mathematical models and information technology for spatial analysis of greenhouse gas emissions from fossil fuel consumption of heat/power plants and households have been developed in consideration of the territorial distribution of greenhouse gas emission sources and structure of statistical data for the Polish voivodships: lubelskie, podkarpackie, podlaskie, and świętokrzyskie. The results of spatial analysis for these eastern voivodeships are presented in the form of thematic maps.

K e y w o r d s: information technology, spatial analysis, greenhouse gas emissions, heat/power plant, residential sector, fossil fuel.

INTRODUCTION

Global warming is a widely discussed problem in the societies and scientific communities all over the world. Most of scientists assert that the increase in concentration of anthropogenic greenhouse gases (GHGs) in the atmosphere is the main reason of global warming. That is why an agreement in the reduction of GHG emissions is a primary issue of international negotiations. Assessing GHG emissions accurately is of high importance to verify fulfilment of international obligations.

To estimate the effectiveness of GHG emission reduction measures one must have information on GHG sources and sinks at the level of individual regions, not only at the national (country) level. Therefore, countries are encouraged to develop their own mathematical models to assess the emission/absorption processes of GHGs. The results of GHG spatial inventory could be used to support decision and policy-making. They allow identifying, under competitive financial conditions, those economic activities which perform the best area-thematic scales from an emission trading point of view. The Ukrainian scientists as well as those from other countries [3, 4, 8, 6, 12, 10, 2, 5, 9] have made a large contribution to the creation of mathematical models for spatial analysis of GHG emissions in different sectors of human activity. These mathematical models were developed for a certain regions and consider the specifics of emission sources regionally. The development of mathematical models for spatial analysis of GHG emissions for other countries/regions is a relevant task.

In Polish regions the spatial GHG inventory has not been conducted that would fully encompass a certain sector of human activity. For example, in the lubelskie and podkarpackie voivodeships spatial GHG inventory has been done only in "residential sector", which is a source category in the Energy sector [20, 16]. So, there is a need to modify the mathematical models for GHG spatial inventory taking into account regional characteristics and structure of statistical data on the economic activity of other regions.

This paper focuses on the spatial analysis of GHG emissions in eastern Polish regions from two types of sources: heat/power plants as huge point sources and residential sector as area sources.

GHG INVENTORY IN POLAND

Annually Poland produces GHG inventory reports as a part of its international obligations (the Kyoto Protocol to the United Nations Framework Convention on Climate Change – UNFCCC). According to the latest national inventory report 2011 [13, 18, 19] the subsector "1.A.1.a Public Electricity and Heat Production" is the largest contributor to emissions. It covers over 95% of total GHG emissions in the Energy sector. The use of solid fuels is dominant (mainly hard coal and lignite). In 2009, the use of hard coal was almost 62% of the entire energy of all fuels used in this subsector (1.A.1.a).

Lignite made approximately 30% of the energy, accordingly. Despite the significant share of solid fuels (approximately 93%) in the total energy related fuel use, a slow decreasing trend can be noticed since the late 1990s (from about 98% in 1998 till 93% in 2009). At the same time, the share of gas as well as the share of biomass has increased in the last decade. The internal load production of heat and power plants, according to the source classification by IPCC (the Intergovernmental Panel on Climate Change) are included in another category of the Energy sector: "1.A.2. Manufacturing Industries and Construction". However, most of these plants generate energy/heat not only for their own use but for residential consumers as well. So, sometimes it is difficult to identify to which category this plant should be included. That is why this article focuses not only on public heat/power plants but also on entities producing for internal needs. The study covers the following greenhouse gases: carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O).

GHG emissions from fossil fuel burned by households (residential sector) are around 10 % of national totals. During the last 2 decades GHG emissions in this category are reported to be decreasing due to the increasing use of gaseous fuels.

CHARACTERISTICS OF ADMINISTRATIVE DIVISION

The territory of Poland is divided into the following administrative units: voivodeships (in Polish – województwo), provinces (in Polish – powiat) and communes (in Polish – gmina). Voivodeship is the largest territorial and administrative unit in Poland. Province is a unit with local government. Commune is the smallest administrative unit in Poland, for example a city, a village or a group of villages and towns. In total, Poland has 16 voivodeships, which are divided into 308 provinces, and the last one into 2469 gminas.

The Polish voivodeships: lubelskie, podkarpackie, podlaskie and świętokrzyskie are located in the eastern part of Poland. A partial spatial inventory of GHGs, namely only in the category of households has already been made for the lubelskie and podkarpackie voivodeships [20, 16]. For the two other voivodeships (podlaskie and świętokrzyskie) that are also located in the eastern Polish region the spatial inventory of GHGs has not been done before.

GHG INVENTORY IN THE ENERGY SECTOR

Most of the estimates of carbon dioxide emissions in the Energy sector are based on data concerning fossil fuel consumption. Emissions are calculated as the product of amount of fuel burned and emission factors, that take into account the carbon content and fuel consumption efficiency (for example, the proportion of fuel that is not oxidized). Fuel fraction which is not oxidized is quite small in modern systems of fuel consumption. The IPCC recommends the assumption that 100% of carbon in fuel is oxidized. The amount of consumed fuel could be measured but it is really difficult to measure carbon content. There is a good correlation between the share of carbon in the fuel and amount of energy released from burning, so the transfer of consumed fuel per unit of mass or volume to energy units enables to take into account its carbon content [1].

Quantity of consumed biomass (biofuels) is reported according to the UNFCCC, but the corresponding emission of carbon dioxide – is not. In the process of growing, biomass absorbs CO_2 from the atmosphere, but when it is burned the gas is emitted again to the atmosphere. Therefore, the resulting emissions are considered to be "zero". However, emissions from consumed fossil fuel during processes of production, harvesting and transporting biomass are reported in the appropriate categories. When biomass is combined with another type of fuel or waste, emissions caused by the burning part of the other fuels are only reported. When, for example, pure ethanol is combined with gasoline as fuel, only the emissions caused by gasoline consumption are reported.

Carbon dioxide emissions are estimated using the next steps [1, 22, 23]:

- analysis of the energy sources in the region,
- calculation of carbon in conventional units,
- assessment of contained carbon in products that are made from fossil fuels,
- calculation of the share of burning carbon,
- calculation of CO_2 emissions for all fuels.

Carbon dioxide emissions are calculated as the product of quantity of consumed fuel, the calorific value, and the rate of oxidation. The general formula for calculating CO_2 emissions (IPCC, 2006):

$$E = D_{stat} \cdot K_{en} \cdot K_{C} \cdot F_{C}, \quad (1)$$

where: E is the amount of emission, Gg; D_{stat} are the activity data in physical units, t; K_{en} is the amount of energy released during combustion of 1 ton of material, J/t; K_C are the emissions of carbon dioxide per unit of obtained energy, Gg/J; F_C is the carbon oxidation factor (in numerical experiments realized it was assumed that $F_C = 1$).

For different categories of human activities and properties of different fuel types these parameters have different values. For better estimation of GHG emissions it is recommended to use emissions factors that were estimated for a certain region and category.

For other greenhouse gases (CH_4, N_2O) emission estimates are based on statistical data for various sectors of human activity. The amount of emissions depends on fuel type, processes, and conditions of production, type of equipment, and methods of monitoring.

Emissions of N_2O, CH_4 and other gases are estimated by the next steps:

- estimating an amount of consumed fuel per year for the certain human activity;
- estimating the basic factors for each type of activity;
- calculating emissions.

The structure of statistical information on consumption of fossil fuels by category in the Polish regions is [21]:

- heat/power plants (according to the IPCC sector classification - 1.A.1),
- industrial boilers and other heating units (1.A.1),
- non-industrial boiler-houses (1.A.1),
- industry and manufacturing (1.A.2),
- transport (road, rail, etc.) (1.A.3),
- other sectors including: agriculture and forestry, households, and other (1.A.5).

To carry out spatial analysis of GHG emissions the geographic information system (GIS) was used. GIS allows forming a database on GHG emission sources as geographic features that are characterized with spatial coordinates and results of simulation on digital maps.

As input data for spatial inventory the digital maps were used with information on administrative division and population, and statistical data on the consumption of fossil fuels obtained from special yearbooks prepared by State Departments of Statistics in each Polish region. Based on these data, the spatial (georeferenced) database was created. The process of spatial analysis of emission is divided into the following steps:

1) collecting statistical data and forming input databases (for example, Excel, Oracle or Access),

2) splitting the digital maps of investigated areas into elementary objects using grids (for example, grid with the resolution of 2 km x 2 km) and disaggregating data on population proportionally to the area of newly created objects,

3) running modules that simulate the processes of greenhouse gas emissions in different sectors of human activity for each elementary object,

4) forming thematic maps that illustrate the spatial distribution of greenhouse gas emissions.

After splitting regional maps into elementary objects the programmed modules that are based on the developed mathematical models calculate emissions from stationary and mobile sources. The final step is the spatial analysis of the achieved thematic maps with information on GHG emissions at the level of elementary objects.

MODELLING OF GREENHOUSE GAS EMISSIONS: HEAT/POWER OR COMBINED HEAT AND POWER PLANTS

In accordance with the structure of national Polish statistics on fossil fuel consumption the stationary emission sources include: heat and power plants, combined heat and power plants; boiler and heating installation of industrial facilities; non-industrial boilers; fuel combustion in industry and construction; fuel combustion in agriculture, forestry and fisheries; households.

Heat and power plants are the largest emission point-type sources. The heat and power supply involves power plants, public and internal load combined heat and power plants, public and municipal heat plants. Public heat and power plants or combined heat and power plants generate energy and heat for residential consumers. Internal load entities generate electricity and heat wholly or partially for their own use.

As statistical data are available only concerning total amounts of consumed fuels by category in each voivodeship, this amount should be disaggregated by a certain parameter. Analysis of statistical publications concerning data on fuel consumption shows that Polish Energy Agency published only amount of coal used by plants (public or internal load) only till 2007, all later publications include only total sum of coal used in all heat/power or combined heat/power plants. So, it was assumed that the proportion between coal used in public and internal load plants in 2007 remained the same for the later years (for example, 2009).

The emissions of an elementary object (point) for a particular voivodeship w_i could be calculated by the following formula:

$$E_{EN,g}(\xi_l) = \sum_{f \in F} \frac{D_{EN,f} \cdot K_{EN,f,en} \cdot K_{EN,f,g,em} \cdot q(\xi_l)}{\sum_{\xi_j \in (\xi_j \cap w_i)} q(\xi_j)}, \qquad (2)$$
$$\xi_l \in \Xi, l = 1,..,L,$$

where: $E_{EN,g}(\xi_l)$ is the emission of gas g from burning fossil fuels by heat and power plants for the elementary object ξ_l that is located in voivodeship w_i; $D_{EN,f}$ is the amount of fuel f burned by heat and power plants; $K_{EN,f,en}, K_{EN,f,g,em}$ are calorification and emission factor of gas g for fuel f burned by heat and power plants; $q(\xi_l)$ is a disaggregation parameter for the point source ξ_l; Ξ is a set of point sources ξ_l, L is a number of elements in the set Ξ.

The choice of disaggregation parameter $q(\xi_l)$ depends on available data on fuel used by plants. For example, for public power plants and heat plants or combined heat and power plants it was assumed that amount of fuels used is proportional to energy or heat production for the year of investigation. If there is no data available on energy and heat production for every plant for a certain voivodeship, the power of a plant was taken as a disaggregation parameter.

In case of autoproducing plants there is a huge lack of information. So, for every voivodeship the approach was different. The first step was figuring out the main emission sources in this region upon analysis the environmental reports. The second step was checking whether this list contains internal load plants: if not – the emissions from internal load plants are negligible, and the fuels used could be disaggregated equally; if yes – the corresponded coefficient should be chosen to this main emitters, and the rest of fuels used should be disaggregated equally by other small sources.

MODELLING OF GREENHOUSE GAS EMISSIONS: RESIDENTIAL SECTOR

In contrast to heat/power plants, the residential sector covers areas of settlement as area type sources. The general approach for GHG spatial inventorying in residential sector involves allocating amount of fuel burned by residents and spatial localization of the corresponding emissions. Specific emission factors for GHGs that take into account fossil fuels characteristics and technology of combustion should be considered. While estimating emissions in the living areas (for a particular city or region as a whole) it is difficult to calculate emissions from fossil fuel burning at a particular house or apartment due to the lack of statistical information. In addition, such detailed information is not necessary because our research is conducted at the level of elementary objects that are created by splitting grid with a specified resolution. Therefore, the sources of GHG emissions in residential sector are considered to be some residential areas (settlements). At the level of an elementary object, emissions are calculated as the sum of emissions from all sources that are partially or fully located in its territory (for example, one elementary object could contain two or more villages and a part of a city).

The following formulas estimate emissions for a certain gas g in households for elementary object δ_n that is located in voivodeship w_i:

$$E_{RES,g}\left(\delta_n\right) = \sum_{f \in F} D_{RES,g,f}\left(\delta_n\right) \cdot \cdot K_{RES,f,en} \cdot K_{RES,g,f,em}, \delta_n \in \Delta, n = \overline{1,N}, \quad (3)$$

$$D_{RES,g,f}\left(\delta_n\right) = \sum_{s \in \tilde{S}^{Rur}} \left(D_{RES,g,f}\left(w_i\right) \cdot I_{RUR,f,g}\left(w_i\right) \times \times \frac{p(s) \cdot area(s \hat{\cap} \delta_n)}{area(s)}\right) + \sum_{s \in \tilde{S}^{\mathrm{Urb}}} \left(D_{RES,g,f}\left(w_i\right) \cdot I_{URB,f,g}\left(w_i\right) \times \times \frac{p(s) \cdot area(s \hat{\cap} \delta_n)}{area(s)}\right), \quad (4)$$

where: $D_{RES,g,f}(w_i)$ is an amount of fuel f burned in voivodeship w_i; $D_{RES,g,f}(\delta_n)$ is an amount of fuel f burned in elementary object δ_n; $K_{RES,f,en}, K_{RES,f,g,em}$ are calorification and emission factor of gas g for fuel f burned in residential sector; Δ is a set of elementary objects δ_n; N is a cardinality of Δ; $p(s)$ is a population of settlement s; $I_{URB,f,g}\left(w_i\right)$, $I_{RUR,f,g}\left(w_i\right)$ are the coefficients that show the fraction of fossil fuel for urban and rural areas, respectively (per resident) of total fuel used in voivodeship; $\tilde{S}^{Urb} = \left\{S_1^{Urb},...\right\}$, $\tilde{S}^{Rur} = \left\{S_1^{Rur},...\right\}$ are the sets of urban and rural settlements respectively; $area(s)$ is an area of settlement s.

The described model requires the following data:

- national energy statistics data:
  - country-specific emission factors for the residential sector and fuel for each gas [17],
  - data on the amount of fuel combusted in the residential sector [21],
  - data on the population for settlements [14, 15],
- GIS-based data:
  - digital map of administrative division in Poland (voivodeships, provinces and communes).

COMPUTER REALIZATIONS

Geoinformation technology based on the developed mathematical models was created using GIS tools. With its help the spatial analysis of CO_2, N_2O, and CH_4 emissions in the categories of energy production and residential sector for eastern Polish region (lubelskie, podkarpackie, podlaskie and świętokrzyskie voivodeships) was performed. The results were presented in the form of thematic maps.

As input data a specialized file (in Excel format) was created. It consists of several sheets: sheet 1 contains data on the fossil fuels consumption for the voivodeships and for all types of power plans; sheet 2 contains information on public plants; sheet 3 contains information on internal load plants; sheet 4 contains information on fuel combusted by regions for each fuel; sheet 5 contains emission factors by source category and fuel used; sheet 6 – remarks and references.

Also, the digital maps with information on geographical borders of Polish voivodships, provinces, and communes (area objects), as well as settlements (point objects), were used as input data. Based on methodology described in the previous section four program modules were created: 1) disaggregation of fuel used in public heat, power, and combined heat and power plants; 2) disaggregation of fuel used in internal load heat/power, and combined heat and power plants; 4) disaggregation of fossil fuel used in residential sector; 5) calculation of emissions.

Figure 1 presents the geographical distribution of main power/heat plants and combined power and heat plants that use coal or natural gas for electricity generation in eastern Polish region. One of the main features of energy/heat production in Poland is high dependence on coal that characterizes the large GHG emission factors.

Figure 2 lists the Polish provinces of eastern regions with the largest GHG emissions that emitted more than 100 000 tones in CO_2 – eqv. The largest emissions were observed in Polaniec, Świętokrzyskie Voivodeship. According to the statistics, in this voivodeship public plants used a lot of coal for energy and heat generation. The combined heat and energy plant in Polaniec consumed most of this amount of coal as it is the fifth largest plant in whole Poland [11].

Other large emission sources in eastern Polish are very powerful combined and heat power plants in the

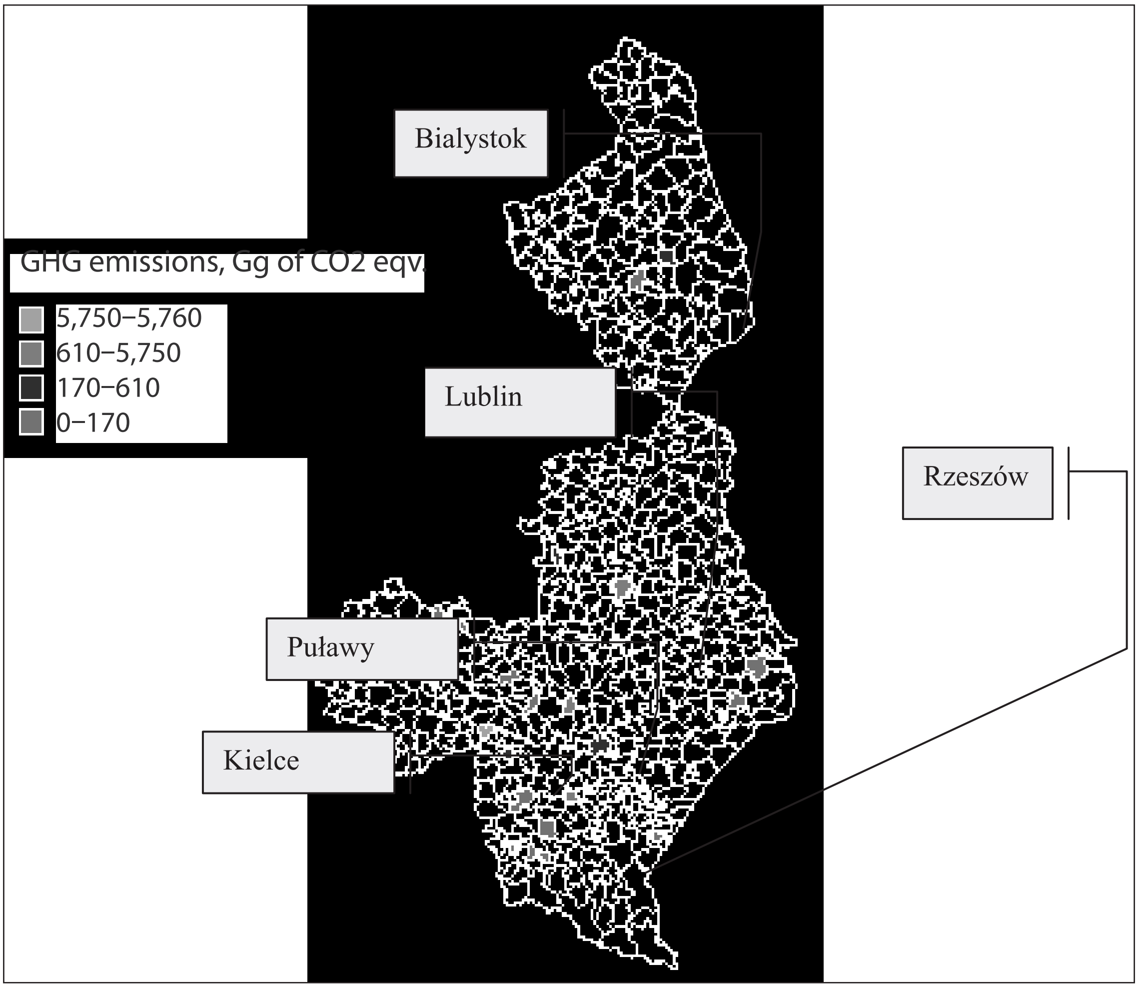

Fig. 1. Main sources of greenhouse gas emissions in eastern Polish region: Electricity production

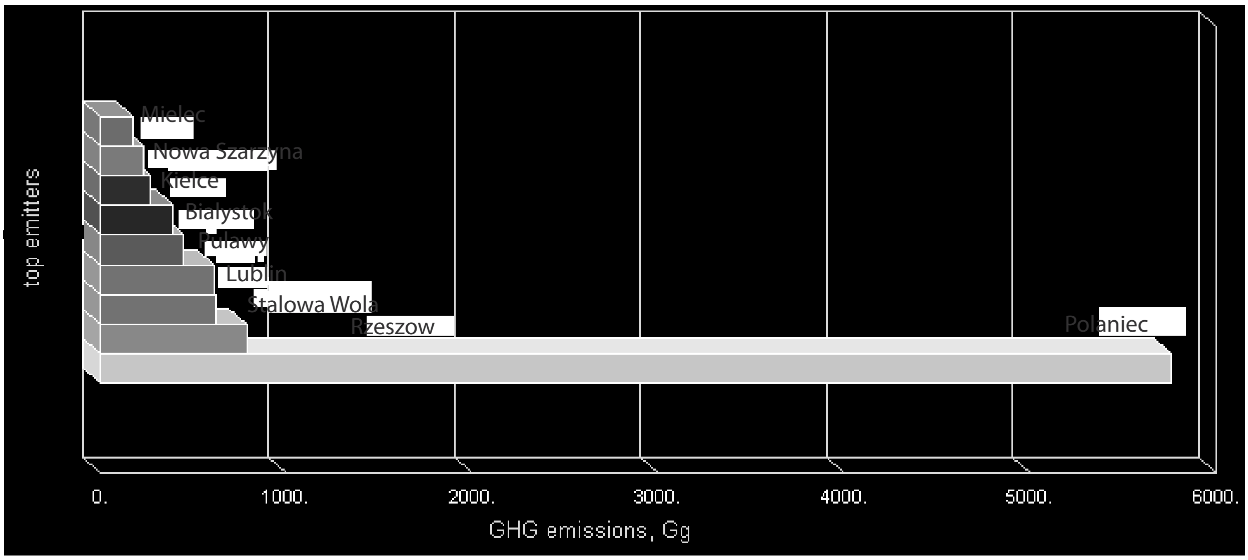

Fig. 2. Top-largest sources of greenhouse gas emissions (>100 Mg of CO_2eqv.)

lubelskie voivodeship, such as Lublin-Wrotków Sp. Z; internal load combined heat /power plant Zaklady Azotowe PUŁAWY S.A. (only coal); and MEGATEM - EC Lublin Sp. z o.o. (mainly natural gas); etc. In total, the greatest greenhouse gas emissions were observed in the świętokrzyskie voivodeship (Polaniec) due to the high coal consumption.

The results of GHG spatial inventory in the residential sector are presented in *Figure 3*. The largest GHG emissions were observed in Lublin, the capital of the lubelskie voivodeship. The largest specific emissions (per square km) were also observed in the lubelskie voivodeship. The shares of particular voivodeships' GHG emissions in total emissions of the eastern Polish regions are: 34,57% for the lubelskie voivodeship, 32,78% for the podkarpackie voivodeship and 19,36% for the świętokrzyskie voivodeship. The lowest emissions are in the podlaskie voivodeship – 13,29%. The results in *figure 3* were obtained at the level of elementary objects created by the grid with resolution 10km.

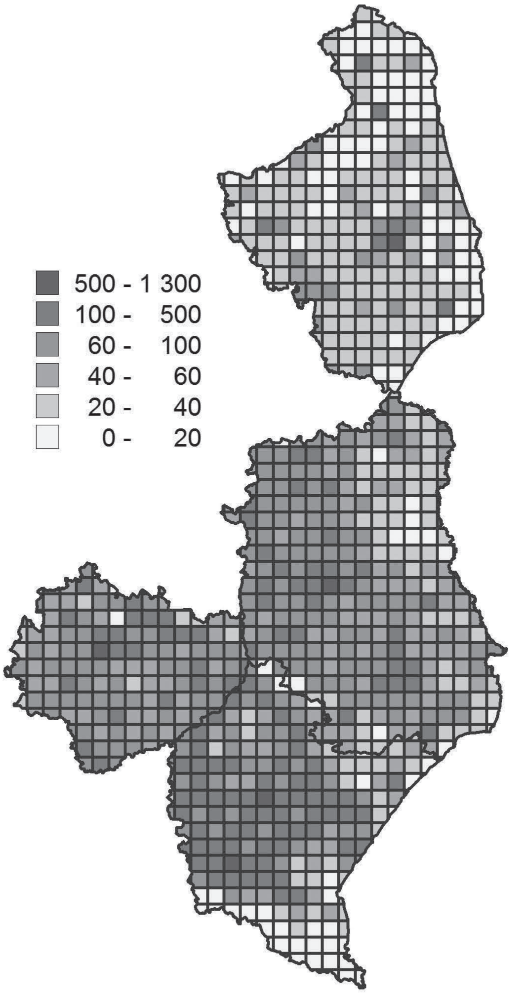

Fig. 3. Total GHG emissions in CO_2-equivalent (t/sq.km) in residential sector

CONCLUSIONS

The mathematical models for greenhouse gas spatial inventory and corresponding geoinformational technology were developed concerning the structure of statistical information and specificity of emission sources of area and point types. The developed models reflect processes of GHG emissions from stationary sources: power/heat plants, and combined heat and power plants, fossil fuel consumption in households. Based on the presented mathematical models of emission processes, the corresponding software modules were programmed using GIS tools. The spatial analysis of CO_2, N_2O, CH_4 emissions of point-type and area-type sources were carried out for the voivodeships: lubelskie, podkarpackie, podlaskie and świętokrzyskie. The results are presented in the form of digital maps.

The distribution of GHG emission sources in eastern Polish voivodeships is very uneven. The largest point-type emission sources are located in świętokrzyskie, podkarpackie and lubelskie voivodeships. For example, the power station in Polaniec, two powerful heat/power plants in Lublin, the similar plants in Rzeszów and Stalowa Wola, Puławy and Białystok, Nowa Sarzyna, Mielec and Kielce. The largest area-type source in residential sector is Lublin, the capital of Lublin vovivodeship. The achieved results are useful for economical and ecological decision-making for effective ways of low carbon development.

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