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Mathematical modeling and spatial analysis of emission processes in Polish industry sector: cement, lime and glass production

N. Charkovska[1)], R. Bun[1)], Z. Nahorski[2)], J. Horabik[2)]

[1)] Lviv Polytechnic National University; e-mail: nadiya.fedyshyn@gmail.com
[2)] Systems Research Institute of Polish Academy of Sciences

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Abstract. The main GHG emission sources in IPCC subsector Mineral Products of Industrial Processes sector in Poland are analyzed, using the developed mathematical models and program tools for emission assesment in production of cement, lime and glass. Results of spatial analysis are presented as digital maps at the levels of particular plants and whole voivodeships.

Key words: mathematical modeling, spatial analysis, GHG emissions, mineral products, industrial sector.

INTRODUCTION

Climate changes are among the most discussed global environmental problems. Scientists argue that the emergence of the greenhouse effect and the destruction of ozone in the stratosphere are the results of increased concentrations of anthropogenic greenhouse gases (GHG) in the atmosphere. The intensive GHG emissions cause increase of the average temperature and warming on the planet. A global community has signed a number of international agreements to reduce level of emissions, and among them the Kyoto protocol, adopted in 1997. The main goal of this protocol is to limit GHG emissions and to introduce the trading mechanism of quotas [8]. For verification of compliance with the international obligations, assessment of GHG emissions plays a crucial role.

A national GHG inventory of IPCC methodology provides estimation of emissions on a country level. This type of inventory allows for comparisons among countries, which is indispensable for signing international agreements. However, for effective emission reduction, information on GHG emission sources is required not only for whole countries, but also for various regions. To carry out analysis of GHG emissions in sufficiently small parts of territory, a spatially distributed inventory can be applied. A considerable advantage of this approach is a possibility to use local specific emission factors, e.g. for specific enterprises. Moreover, results of a spatially distributed inventory can be used by governmental agencies to plan development strategies for individual regions.

A large contribution to the creation of geoinformation technologies and respective mathematical models of GHG emission/absorption processes in different sectors of human activity (energy sector, industry, agriculture, transport, forestry) is due to the PhD theses by Bun, Boychuk (Hamal), and Lesiv [2, 6, 9]. These works can serve as the basis for a construction of spatial GHG inventories. So far, mathematical models for Western Ukraine, and particularly Lviv region, have been created [3]. They take into account specificity of GHG emission sources in this region. In this paper we develop the models and methods of spatial GHG inventory for regions of Poland, see also [10].

Emission processes from the industrial sector of Ukraine have been partly investigated in [18]. To the best of our knowledge, GHG spatial inventory for the industrial sector of Poland has not yet been carried out.

This paper is focused on GHG emissions from large point sources, such as cement, glass and lime production.

GHG INVENTORY IN POLAND

Every year Poland reports on GHG emissions in the national inventory reports (NIR), which are used to certify fulfillment of international obligations. CO_2 emissions from the cement industry amount to 5% of the total GHG emissions. Approximately 50% of these emissions are caused by industrial chemical processes, and the remainder comes from the fuel combustion in the cement production, being included in the Energy sector. According to the Polish national inventory report 2010, the emissions of carbon dioxide (CO_2) from cement production amounted to 6693 thousand tons (2.A.1 Cement Production). It covers 1.7% of total GHG emissions in the industrial sector, and 68% in the subsector Mineral Products [11].

CO_2 emissions from lime production (2.A.2 Lime Production) in 2008 amounted to 1.5 thousand tons, and were reduced twice compared with 1988. This is due to a diminished production of lime in Poland over the past two decades.

CO_2 emissions from production of glass and glass fiber (2.A.7 Other: Glass Production) amounted to 344.9 thousand tons in 2008. These emissions increase annually due to an increase of production in the sector of innovative technologies and launching floatation of new enterprises producing various types of glass.

Below we describe the method of spatial inventory, which takes into account the administrative structure of Poland as well as location of individual plants. The territory of Poland is divided into the following administrative units – voivodeships, districts (in Polish "powiat"), and municipalities (in Polish "gmina"). A voivodeship is the largest administrative and territorial unit in Poland. A district is a governmental and administrative unit of the second (middle) level. A municipality is the smallest administrative unit of the third level, for example, a city, a village or a group of villages or cities. Poland consists of 16 voivodeships, 308 districts, 65 of which are cities with the district rights, and 2478 municipalities.

MODELLING OF EMISSION PROCESSES IN THE CATEGORY CEMENT PRODUCTION

Polish cement industry is located in 7 voivodeships. There are 11 cement production plants with full production cycle, 1 cement grinding plant, and 1 alumina cement production plant [20]. Plants with the full production cycle include the stages of the clinker calcination and cement grinding. The largest three groups are Górażdże Cement S.A. (concern Heidelberg), Lafarge Cement S.A. (concern Lafarge), and Grupa Ożarów S.A. (concern CRH). The shares of these groups in total cement production are 26%, 21% and 17%, respectively.

CO_2 emissions from cement production occur during the production of clinker, which is an intermediate component in the cement manufacturing process [19]. During the production of clinker, limestone, which consists mainly of calcium carbonate $CaCO_3$, in 95%, is calcined to produce lime CaO, and CO_2 as a by-product. The CaO then reacts with silica, aluminium and iron oxides in the raw materials to make the clinker minerals, which are dominantly hydraulic calcium silicates. In these reactions, CO_2 is not emitted any further.

The main challenge in the estimation of CO_2 emissions from cement production is to deal with a varying CaO content in clinker. A good practice is to estimate CO_2 emissions using data for clinker production as well as for the CaO content of the clinker, and to correct for the loss of the so-called cement kiln dust (CKD) [???]. This approach assumes that 100% of the CaO comes from a carbonate source (e.g. $CaCO_3$ in limestone). CKD may be recycled to the kiln partially or completely. Any CKD that is not recycled can be considered lost to the system in terms of CO_2 emissions.

In terms of GHG inventory, each cement plant is considered as a point-type source of emissions. Carbon dioxide emission from a single point source is calculated as a product of the quantity of clinker produced, CaO content of clinker, and cement kiln dust losses — according to the formula below:

$$E_{Cem}^{CO_2}(\xi_n) = F_{stat_{CEM}}(\xi_n) \cdot K_{Clinker}^{CO_2} \cdot K_{CKD},$$
$$\xi_n \in \Xi_{CEM}, n = 1, ..., N, \quad (1)$$

where:

$E_{Cem}^{CO_2}$ is the amount of carbon oxide emissions from the cement plant ξ_n,

$F_{stat_{CEM}}$ are the activity data on (the quantity of) clinker production for the cement plant ξ_n in physical units, Mg,

$K_{Clinker}^{CO_2}$ is the emission factor for clinker;

K_{CKD} is the correction factor for losses of cement kiln dust (it was assumed that $K_{CKD} = 1.02$),

Ξ_{CEM} is the set of cement production plants,

N is the number of these plants.

Emission factor $K_{Clinker}^{CO_2}$ is calculated as the ratio of the mass of CO_2 emitted to the atmosphere from a unit mass of clinker. Traditionally, this coefficient is represented in kg CO_2 per tonne of clinker. In this study it was accepted that $K_{Clinker}^{CO_2} = 529\ kg_{CO2} / t$ [11].

The amount of produced clinker/cement is known on the national level according to GUS yearbooks [12, 15]. The information about capacities of cement plants is also available [7]. The Polish Cement Association reports data for the cement industry in a special yearbook (Informator SPC). The yearbook for 2010 contains a diagram with the shares of the cement groups in Polish cement production sector in 2009 [20]. Amount of cement produced in the country in 2010 is distributed between the groups according to their share in the total production. Using the capacities of each plant, the total capacity and the annual output of cement produced in 2010, the amount of cement produced by each plant is calculated proportionally to its capacity.

MODELLING OF EMISSION PROCESSES IN THE CATEGORY LIME PRODUCTION

The quantity of lime/quicklime produced in Poland amounted to 1798.9 thousand tons in 2010 [12]. There are 7 large industrial groups in Poland which quarry limestone, and based on it produce different types of lime (quicklime, slaked lime, dry calcium hydroxide powder, milk of lime, lime putty, etc.) [17]. Germany, France, Poland, Belgium, Spain and Italy are the largest producers of lime in the EU-27, altogether accounting for about 20% of the world's total lime production [14].

Lime production emits CO_2 through the thermal decomposition (calcination) of the calcium carbonate $CaCO_3$ in the limestone to produce quicklime CaO, or through the decomposition of dolomite $CaCO_3 \cdot MgCO_3$ to produce dolomitic quicklime $CaO \cdot MgO$. A good practice for emission estimation from lime production is to determine the complete production of CaO and $CaO \cdot MgO$ from data on lime production [19].

Carbon dioxide emissions are calculated as the product of the quantity of produced lime and the emission factor for lime.

Similarly as cement plants, the lime production plants are also represented as point-type emission sources. To perform an inventory for this source category, we use the following model:

$$E^{CO_2}_{Lime}(\xi_l) = F_{stat_{LIME}}(\xi_l) \cdot K^{CO_2}_{Lime},$$
$$\xi_l \in \Xi_{LIME},\ l = 1, ..., L, \qquad (2)$$

where:

$E^{CO_2}_{Lime}$ is the amount of carbon oxide emissions from the lime production plant ξ_l,

$F_{stat_{LIME}}$ is the activity data on (quantity of) lime production for the plant ξ_l in physical units, t,

$K^{CO_2}_{Lime}$ is the emission factor for quicklime (including the dolomite quicklime); it was assumed that CO_2 emission factor is equal to 785 kg CO_2 per tonne of lime [11],

Ξ_{LIME} is the set of lime production plants;

L is the number of these plants.

For different types of quicklime, with high content of calcium or dolomite, emission factors may vary. The above model can be applied on the level of lime production plants, provided that detailed data are available.

MODELLING OF EMISSION PROCESSES IN THE CATEGORY GLASS PRODUCTION

In Poland, 30 plants in 11 voivodships produce different types of glass (Figure 1). A list of the largest producers of container glass is available on the forum [16]. Employers' Association "Polish Glass" published a document that provides an overview of the glass industry in Poland, the EU and also the glass production technology [13].

Various types of glass products are used in industry. The glass industry is divided into four main categories, such as container glass, flat glass, fiber glass and special glass [19]. Container glass is the largest sector of the glass industry in the EU, and its share in the total production is approximately 50 – 60% depending on the year. Flat glass is the second largest sector of the glass industry with its share of above 29% (2007). The share of special glass amounts to 2.1%, and the share of fiber glass reaches up to 10% (2005) [1].

Only the above mentioned types of glass are considered in the IPCC methodology [19]. However, it should be noted that the domestic and crystal glasses are also produced in Poland. That is why in our calculations emissions from the production of domestic glass were included in this category.

Carbon dioxide CO_2 is emitted in the melting process of raw materials. Limestone $CaCO_3$, dolomite $CaMg(CO_3)_2$ and soda ash Na_2CO_3 are the biggest components of these raw materials, and they are quarried as carbonate minerals for the glass industry. They represent primary CO_2 emissions, and therefore they are included in the assessment of emissions [19].

The behavior of these carbonates in the melting process of glass is a complex high-temperature reaction, which can not be directly compared with the calcination of carbonates to produce quicklime (dolomitic lime). However, this process, carried out in around 1500°C, gives the same net-effect in terms of CO_2 emissions. In practice, the glass is made not only from raw materials. A certain amount of scrap glass (cullet) is also added to these minerals. Cullet is usually used in the most profitable amount, but sometimes limitations are imposed

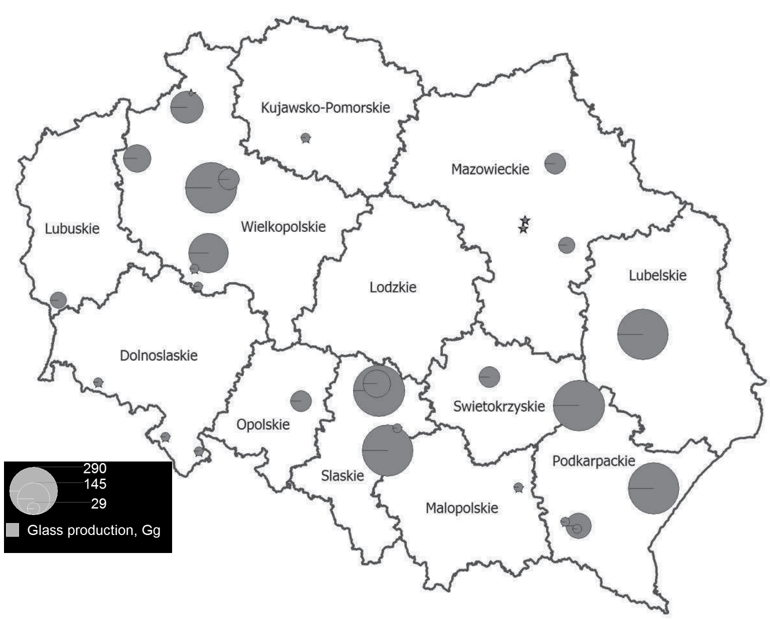

Fig. 1. Territorial distribution of glass production plants with a capacity more than 20 tons per day (thousand tons, 2010)

on its usage. For example, a maximum share of cullet for the container glass (percentage of cullet in the glass batch) is 40% – 60%. Usually, also manufacturers of the dielectric fiber glass use less cullet. Cullet comes from two sources: (1) the return of defective or broken glass from the own plant in the production process; (2) from outside sources (the recyclable usage program or the brokerage services). The latter source of supply is more important for developed economies, and less important for developing countries, where utilization of glass is not so widespread.

In terms of GHG emissions from glass production, the plants are also treated as the point-type sources of emissions. For the purpose of GHG spatial inventory, the mathematical model has been used:

$$E_{Glass}^{CO_2}\left(\xi_g\right)=\sum_{i=1}^{I}F_{stat_{GLASS},i}\left(\xi_g\right)\cdot K_{Glass,i}^{CO_2}\cdot\left(1-K_{CR,i}\right),$$

$$\xi_g\in\Xi_{GLASS},\,g=1,\ldots,G, \qquad (3)$$

where:

$E_{Glass}^{CO_2}$ is the amount of carbon oxide emissions from the glass production plant ξ_g,

$F_{stat_{GLASS},i}$ is the activity of the production of the glass of type i for the plant ξ_g in physical units, Mg,

$K_{Glass,i}^{CO_2}$ is the emission factor for the glass of type i (usually CO_2 emission from the production of the mass unit of glass are measured as ton of CO_2 per ton of glass),

$K_{CR,i}$ is the cullet ratio for the production of the glass of type i (in relative units),

I is a quantity of different types of glass, produced in the country,

Ξ_{GLASS} is the set of glass production plants,

G is the number of these plants.

Volumes of production of various types of glass in Poland amounted to 2692.3 thousand tons in 2010 [12]. Information on emission factors and shares of cullet is absent in the Polish national inventory report 2010. These coefficients were taken from the IPCC guideline [19].

NUMERICAL RESULTS

Using a geographic information system (GIS), a geoinformation technology has been developed, in which the above mentioned models (1) – (3) are used to estimate the emissions from the production of main minerals.

Statistical data have been collected, and an input database in the Excel format has been formed (separately for each source category). The tables contain information about names and locations of plants, their production capacities and the specific national emission factors (or, if known, local ones at a level of plants).

To accomplish spatial analysis of greenhouse gas emissions, the digital maps of Polish voivodeships were used, and three software modules have been created. The software allows building digital maps of geographic objects (cement, lime and glass production plants), and simulating emission processes at each of them.

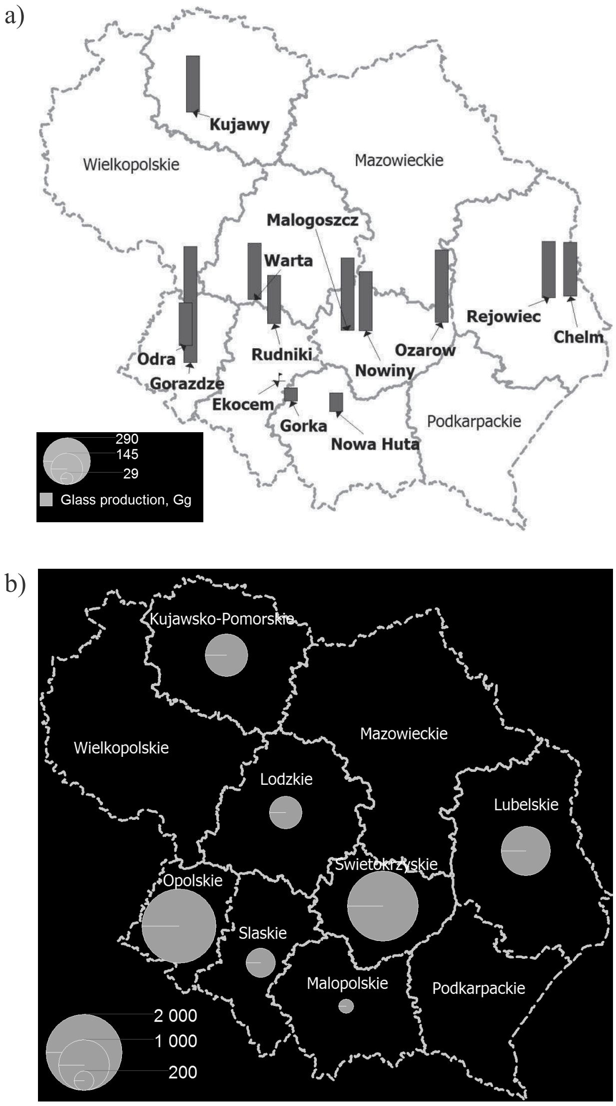

Fig. 2. Main sources of carbon dioxide emissions from the cement production in Poland (thousand tons, 2010): on the plant level (a), on the voivodship level (b)

In Figure 2 the carbon dioxide emissions from the cement production are depicted. Panel a) shows results on the level of plants using the data on the production in 2010, while panel b) presents emissions on the level of voivodships. Three largest emissions sources are the plant Górażdże (1654.1 thousand tons); the plants Małogoszcz and Kujawy (751.8 thousand tons each). The largest emissions of carbon dioxide are concentrated in the Opolskie (1936.1 thousand tons) and Świętokrzyskie (1767 thousand tons) voivodships, and the smallest emissions in the Lesser Poland (Małopolskie) voivodship (113 thousand tons). Such low emissions are associated with the fact that in this province there are operating only 2 plants with small production capacities [4].

Results of spatial GHG inventory from lime production are presented in Figure 3 and Figure 4. In this category, the leaders in terms of emissions are companies Bukowa, Czatkowice and Labtar. The largest CO_2 emissions are concentrated in Świętokrzyskie (403.4 tons), less in Opolskie (336.2 tons), Lesser Poland (201.7 tons), Lower Silesian (Dolnośląskie) (168.1 tons), Kuyavian-Pomeranian (Kujawsko-Pomorskie) and Podlaskie (100.8 tons each), and the smallest in West Pomeranian (Zachodniopomorskie) and Łódzkie (50.4 tons each) voivodships.

Fig. 3. Carbon dioxide emissions from lime production on the level of plants (tons, 2010)

Fig. 4. Carbon dioxide emissions from lime production on the level of voivodships (tons, 2010)

In Figure 5 the emissions from glass production are depicted for the following voivodships: Kuyavian-Pomeranian (1 plant), Lubelskie (1), Opolskie (1), Silesian (Śląskie) (4), Świętokrzyskie (2), Lesser Poland (1), Podkarpackie (4), Masovian (Mazowieckie) (4), Greater Poland (Wielkopolskie) (8), Lower Silesian (3), and Lubuskie (1). The largest emissions of carbon dioxide are reported in Greater Poland (87.9 thousand tons) and Silesian (97.2 thousand tons), while the smallest ones in Lesser Poland and Kuyavian-Pomeranian (0.9 thousand tons each) [5].

Using the developed mathematical models and specialized geographic information system, the inventory of CO_2 emissions in the subsector Mineral Products has been prepared. Results of this inventory are obtained on the level of voivodships. Figure 6 presents total emissions of carbon dioxide from the production of main mineral substances: lime, cement and glass.

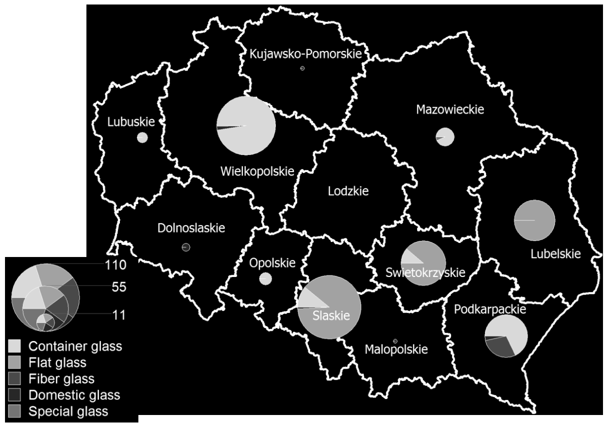

Fig. 5. Structure of CO_2 emissions from production of various types of glass in Poland on the level of voivodships (thousand tons, 2010)

Fig. 6. Total CO_2 emissions from the subsector "Mineral products" on the level of voivodships (tons, 2010)

CONCLUSIONS

Mathematical models for GHG spatial inventory in the subsector Mineral Products have been developed. They reflect the emission processes from stationary (fixed) point-type sources for plants producing cement, glass and lime. The models depend on statistical data and specific national emission factors. The spatial analysis of CO_2 emissions from large point sources has been done for all voivodships of Poland, except for Pomeranian (Pomorskie) and Warmian-Masurian (Warmińsko-Mazurskie), since there is no developed industry of mineral products there. The results are displayed as digital maps.

The results show that the territorial distribution of emission sources is extremely uneven. The largest emissions are observed in Opolskie, Świętokrzyskie and Lubelskie voivodships. For example, two cement production plants, Rejowiec and Chełm (Lubelskie voivodship), emit more than 940 thousand tons of carbon dioxide. The obtained estimates serve as a part of the research conducted within a project aiming at elaboration of emission distribution in Poland with a fine resolution.

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