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ANALYSIS AND SELECTION OF CO_2 SOURCES FOR CCS-EOR PROJECTS IN OIL FIELDS CLUSTERS IN POLAND**

1. INTRODUCTION

Reducing CO_2 emissions from industrial plants that use fossil fuels as their energy source is regarded as one of the major challenges for combating climate change [4]. An option for accomplishing that aim is the CO_2 capture, utilization and storage technology (CCUS). It involves capturing CO_2 from flue gas, transporting it, utilizing it for economically productive activities (CCU – carbon capture and utilization), and/or permanently disposing it in non-atmospheric sinks (CCS carbon capture and storage). Some technologies, such as enhanced oil recovery (EOR) allow simultaneous CCUS [7], because CO_2 is a well-recognized asset in the petroleum industry for the enhancement of oil extraction. Its use for enhanced oil recovery is a process that seeks to improve the flow and recovery rate of hydrocarbon from a reservoir (CO_2-EOR) [5]. Unlike other options for CO_2 utilization (e.g. use as a chemical feedstock), EOR can provide long-term storage and is able to increase the production of an economically valuable resource [6]. CO_2-EOR is expected to produce additional 5–20% of the original oil in place (OOIP) [4] and it is also identified to have a strong potential to reduce the overall CCS cost, however the cost benefits are strongly dependent on the oil price and the considered EOR injection period [2]. CO_2-EOR is usually a large-scale project and requires techno-economic evaluation before its deployment, a particularly important issue in this assessment is the availability of a low-cost source of CO_2. The issue of selection of sources of CO_2 for projects CCS-CO_2-EOR is raised in a number of references [1–2, 4–7].

This article includes a comprehensive selection of emitters, which are appropriate carbon dioxide suppliers for the oil fields clusters (Fig. 1) selected as a part of the project „Multifield CO_2

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storage for environment and energy" (MUSE), which is co-financed by the Polish-Norwegian Research Programme. The idea of CO_2 injection into clusters arises from the fact that oil reservoirs in Poland are relatively small, but very often located close together. Grouping reservoirs allows the potential storage capacity to increase significantly and improves economic indicators.

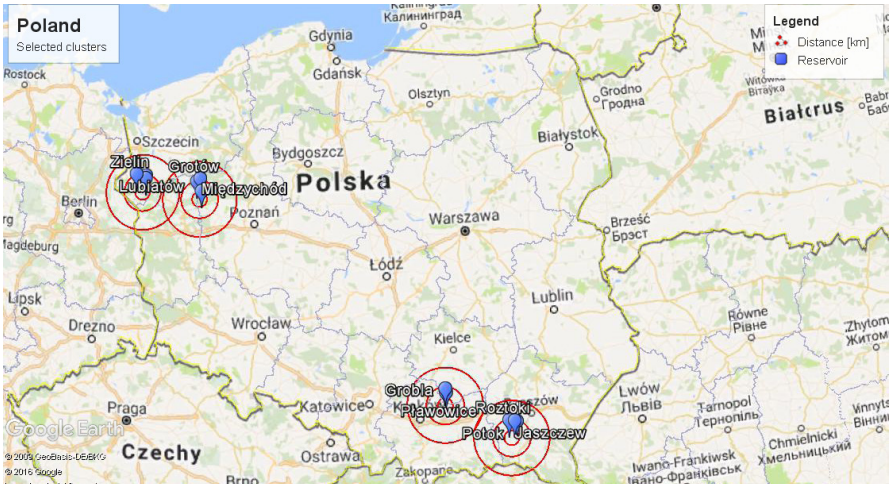

Fig. 1. Location of the selected clusters

Source: Google Earth

Emitters were chosen from the database of all installations registered in Poland (in 2014) generating a minimum of 1 Mg CO_2 per year, which was made available by the Institute of Environmental Protection-National Research Institute. The detailed analysis of this database was presented in the previous article [3]. However, only producers with an annual emission not lower than 10 000 tons of carbon dioxide were taken into account. This limitation is imposed by the volume of CO_2, which is needed to conduct the effective CCS-EOR process on the analyzed clusters. Then emitters number was reduced to these located closer than 50 km from the cluster center. Moreover, three distance groups (area to 10 km from cluster center, from 10 km to 25 km and from 25 km to 50 km) were set for each cluster. Final stage of selection was connected with detailed analysis of emitters. Variety of dimensions was taken into account such as companies emission, which should be appropriate for the cluster demand, type of this emission, which should be permanent (not temporary), installation type – easy to CO_2 capture, kind of the company – typical industrial companies are preferred and distance from the cluster center. Eventually, potential CO_2 suppliers for the considered clusters were selected.

2. SOURCES SELECTION

2.1. Roztoki–Jaszczew–Potok cluster

The cluster containing Roztoki, Jaszczew and Potok reservoirs is located in the southwest area of Subcarpathian Province and close to Lesser Poland Province. Therefore, these

two regions were taken into account during emitters selection. There are 44 and 48 emitters with annual emission greater than 10 000 Mg of CO_2 in Subcarpathian and Lesser Poland Province, respectively. An average annual emission was 107 564 Mg of CO_2, while the median amounted only to 27 719 tons, what indicates an uneven emission distribution.

Table 1

Descriptive statistics of CO_2 emission [Mg] in Subcarpathian and Lesser Poland Provinces

Mean	107 563.98
Median	27 719.00
Minimum	10 085.00
Maximum	1 864 996.00
Sum	9 895 886.00
Count	92

Only 23 emitters are located in the area to 50 km from the center of the cluster (Fig. 2) and they produced 962 108 Mg of CO_2 in 2014. They can be divided into groups by sectors of their activities. Obviously, the energy sector includes the largest number of installations equal to 19, which generated the largest amount of carbon dioxide: 828 456 Mg of CO_2. Installations in this sector generated an average of 43 602 tons of carbon dioxide per year. Two companies from the mineral industry produced 58 427 Mg of CO_2, while chemical industry and waste and sewage management is represented only by one installation each and they annually produced 63 973 Mg of CO_2 and 11 252 Mg of CO_2, respectively.

Fig. 2. Location of the most significant emitters for the Roztoki–Jaszczew–Potok cluster

Source: Institute of Environmental Protection data, Google Earth

There are 7 emitters in the area to 10 km from the cluster center and they additionally produced 223 538 Mg of CO_2. They are located in Jasło (5 installations) and Jedlicze (2 installations). Five installations from the energy sector generated 148 313 Mg of CO_2. One company from the chemical industry produced 63 973 Mg of CO_2, while this from the waste and sewage management emitted 11 252 Mg. However, there are only three emitters in the area from 10 km to 25 km and all of them are located in Krosno. Two installations related to the energy sector generated 52 186 Mg of CO_2. The last one (mineral industry) produced 43 866 tons of carbon dioxide in 2014. In contrast the farthest area (25 km to 50 km from the cluster center) includes 13 emitters. Almost all these installations (12) are related to the energy sector and produced 627 957 Mg of CO_2. Only one installation generating annually 14 561 tons of carbon dioxide is used for the purpose of the mineral industry. In the case of emitters' locations, 4 installations are placed in Rzeszów, 2 in each of Ropczyce, Sanok, Dębica and for 1 in Rudna Mała, Gorlice and Brzozów.

Based on the analysis taking into account distance from the cluster, emission size and type, installation type and kind of the company only two emitters were finally selected (Fig. 3). First emitter is from Jasło (located only 10.2 km from the cluster) and generates 63 973 Mg of CO_2 per year. It produces chemical substances and fertilizers (chemical industry). The second one is a glass manufacturer (mineral industry) and is situated in Krosno (43 866 Mg of CO_2) placed 12.9 km from the cluster center. Emissions generated in 2014 by both these emitters correspond with a demand for carbon dioxide during an injection process.

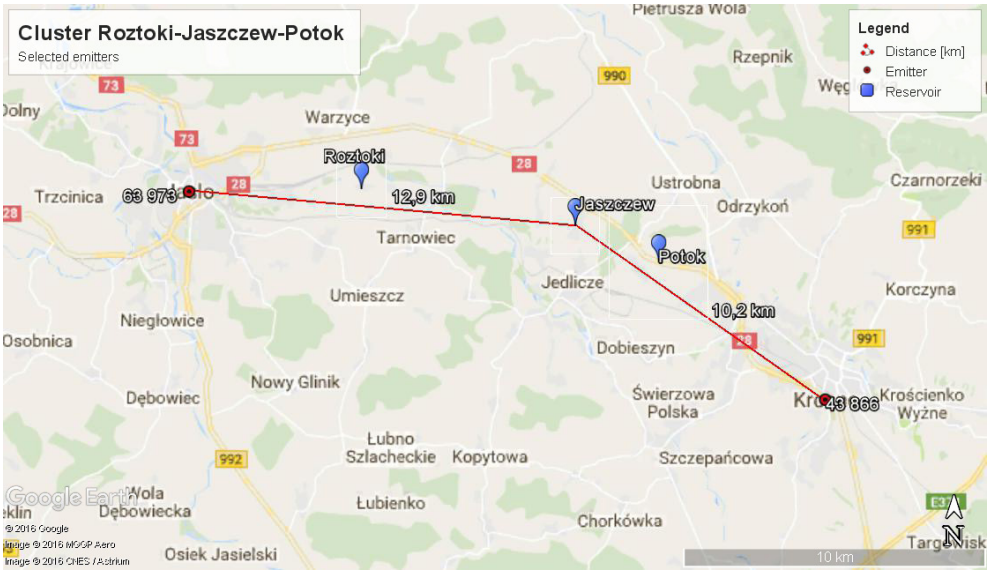

Fig. 3. Location of the selected emitters for the Roztoki–Jaszczew–Potok cluster

Source: Institute of Environmental Protection data, Google Earth

2.2. Pławowice–Grobla cluster

The cluster consisting of Pławowice and Grobla reservoirs is situated in Lesser Poland Province and really close to Świętokrzyskie Province. Hence, installations from these two regions were considered in this analysis (Tab. 2). There are 48 and 43 companies emitting annually more than 10 000 Mg of CO_2 in Lesser Poland Province and Świętokrzyskie Province, respectively. They generated in 2014 significant amount of carbon dioxide that is 19 014 335 Mg what is related with huge urbanizing and industrialization of the analyzed regions. The difference between the average and the median values indicates that the majority of companies emitted considerably less carbon dioxide than average.

Table 2

Descriptive statistics of CO_2 emission [Mg] in Lesser Poland and Świętokrzyskie Provinces

Mean	208 948.74
Median	21 343.00
Minimum	10 354.00
Maximum	6 118 214.00
Sum	19 014 335.00
Count	91

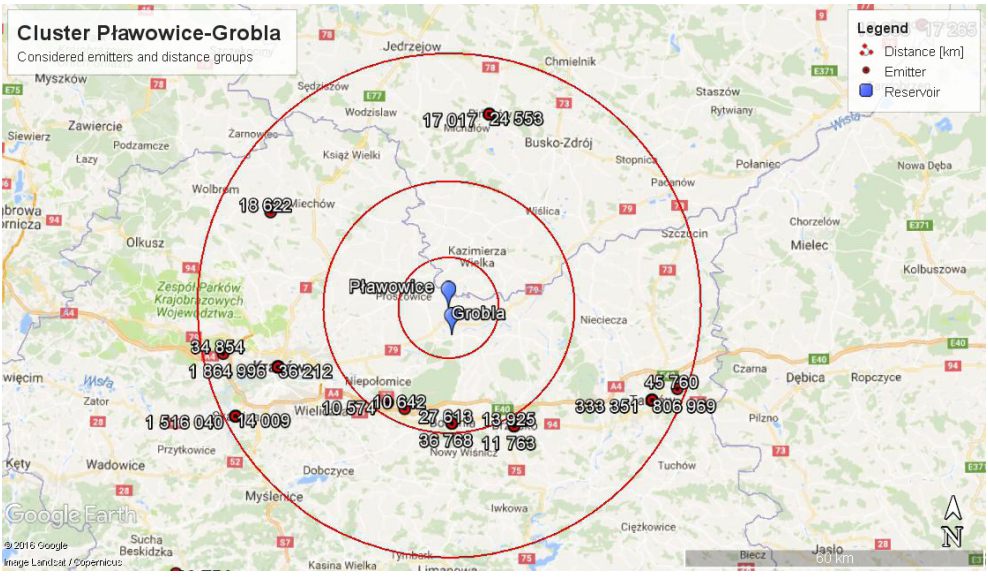

Fig. 4. Location of the most significant emitters for the Pławowice–Grobla cluster

Source: Institute of Environmental Protection data, Google Earth

In the area surrounding the cluster (Fig. 4), there are 25 installations generating 4 956 721 Mg of carbon dioxide per year. Analyzed emitters are related to 6 sectors of their activities (Tab. 3). The major one is the energy sector represented by nearly half of installations generating almost all emission of the analyzed area. It is worth to highlight that the emission of the chemical industry, which has only 2 emitters is nearly 3 time greater than in the mineral industry, which includes 6 companies.

Table 3

The emission structure nearby the Pławowice–Grobla cluster

Sector	Total emission CO_2 [Mg]	Emitters number
Energy sector	4 368 394	12
Mineral industry	138 844	6
Chemical industry	367 876	2
Food industry	24 349	2
Metal production and metalworking	38 636	2
Different activities	18 622	1
Sum	4 956 721	25

The nearest area, which includes regions placed closer than 10 km from the center of the cluster involves pieces of both analyzed provinces. Despite this fact, there are no big enough emitters of carbon dioxide in this area. However, the area from 10 km to 25 km from the cluster center includes 4 installations from Lesser Poland Province. The emitter from Bochnia has two installations – one is used to the metalworking and emitted 27 613 Mg of CO_2, while the other one is connected with the energy sector. Other installations from this area (one from Kłaj and one from Dąbrowa) are also related to this sector, which in 2014 was responsible for 57 984 Mg of CO_2. Moreover, there are 21 installations in the farthest area that is from 25 km to 50 km from the cluster center. Most of them are located in Lesser Poland Province (mainly in Kraków and Tarnów) while only three in Świętokrzyskie Province (all in Pińczów). It is also worth to highlight that emitters structure in the analyzed region is analogous like in Table 3. Two differences are that the energy sector generated in the analyzed area 4 310 410 Mg of carbon dioxide with the use of 9 installations and that the metalworking is represented only by one emitter with emission of 11 023 Mg of CO_2 per year.

After thorough analysis of the appropriate emitters three companies whose annual emissions satisfy the cluster's demand were finally selected as possible suppliers of carbon dioxide (Fig. 5). Producer from Tarnów situated 44,6 km from the cluster center uses two different installations. This with greater annual emission (806 969 Mg of CO_2) is used to the fuel combustion (energy sector), while the second one to the production of chemical compounds (chemical industry) and produced 333 351 Mg of CO_2. Two other emitters are also related to the fuel combustion and generated annually immense amount of carbon dioxide. The company from Kraków produced the biggest value i.e. 1 864 996 Mg of CO_2 and is located closest to the cluster (36.0 km), while this from Skawina (47.5 km from the cluster) in 2014 emitted 1 516 040 Mg of CO_2.

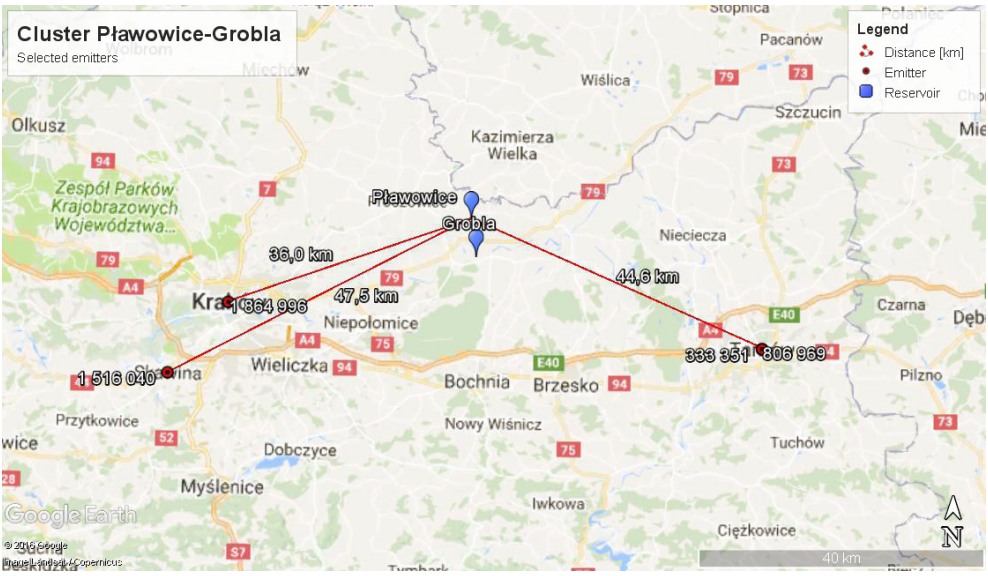

Fig. 5. Location of the selected emitters for the Pławowice–Grobla cluster

Source: Institute of Environmental Protection data, Google Earth

2.3. Lubiatów–Międzychód–Grotów cluster

The analyzed cluster consists of three reservoirs i.e. Lubiatów and Grotów placed in Lubusz Province and Międzychód reservoir located in Greater Poland Province. Moreover, it is situated really close to West Pomeranian Province, so these three provinces were taken into account. There are 126 installations generating annually more than 10 000 Mg of carbon dioxide (Tab. 4). Most of them (80) are placed in Greater Poland Province, because this region is the most expansive and densely populated. Then, 29 installations are situated in West Pomeranian Province and only 17 in Lubusz Province, because these two regions are underpopulated and thickly wooded. All of the analyzed emitters generated in 2014 huge amount of carbon dioxide i.e. 27 068 170 Mg with a considerable gap between the average and the median emissions (uneven emission distribution).

Table 4

Descriptive statistics of CO_2 emission [Mg] in Greater Poland, West Pomeranian and Lubusz Provinces

Mean	214 826.75
Median	28 696.00
Minimum	10 000.00
Maximum	5 259 965.00
Sum	27 068 170.00
Count	126

Although the huge number of installations in the considered provinces, there are only 5 emitters generating 785 341 Mg of CO_2 per year in the vicinity of the cluster (Fig. 5), because it is located in the afforested area. Four emitters are used in the energy sector and produced 715 900 Mg of CO_2, while only one company (69 441 Mg of CO_2) is related to the mineral industry.

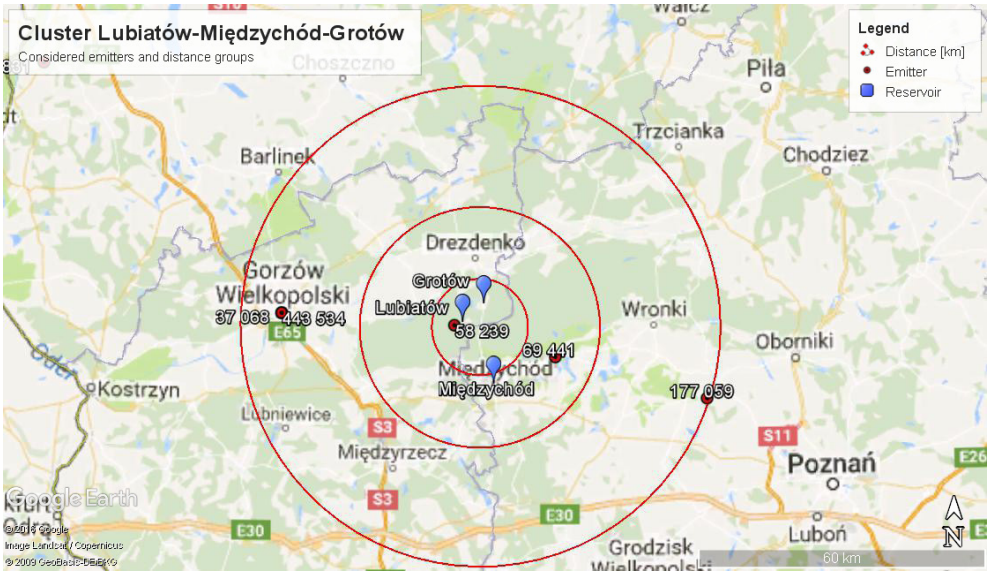

Fig. 6. Location of the most significant emitters for the Lubiatów–Międzychód–Grotów cluster

Source: Institute of Environmental Protection data, Google Earth

There is only one CO_2 emitter in the area to 10 km from the analyzed cluster center, which is located just in Lubiatów. This installation is related to the energy sector and generated 58 239 Mg of CO_2. Moreover, the area from 10 km to 25 km from the center of the cluster also includes only one emitter located in Sieraków. This installation used in the mineral industry generated 69 441 Mg of CO_2 per year. In contrast to nearer areas this from 25 km to 50 km from the cluster center includes three emitters. Two of them are placed in Gorzów Wielkopolski, bigger one emitted annually 443 534 Mg of CO_2, while the other one generated 37 068 Mg in 2014. Last one company is situated in Emilianowo and produced 177 059 Mg of CO_2. What is more, all of these installations are related to the energy sector. At the Figure 6 there is presented the location of the most significant emitters for the Labiatów–Międzychód–Grotów cluster.

Due to the fact that two huge enough emitters are located close to the center of the cluster, three emitters from the farthest area are less appropriate as CO_2 suppliers because of greater transport costs. As the result, two installation were finally selected (Fig. 7). Bigger selected emitter is located in Sieraków (West Pomeranian Province) and distant 16,9 km from the analyzed cluster center. Its installation is used to glass manufacturing (mineral industry) and generated 69 441 Mg of CO_2. The next one producer, whose annual emission is slightly smaller (58 239 Mg of CO_2) is placed exactly in the area of Lubiatów reservoir. This emitter is connected with the fuel combustion process (energy sector).

Fig. 7. Location of the selected emitters for the Lubiatów–Międzychód–Grotów cluster

Source: Institute of Environmental Protection data, Google Earth

2.4. BMB–Zielin cluster

The analyzed cluster consists of two reservoirs i.e. Zielin and Barnówko–Mostno–Buszewo (BMB). This cluster is situated on the borderland between West Pomeranian and Lubusz Provinces, so these two regions were taken into consideration. There are only 46 installations (Tab. 5), because of low urbanizing and significant afforestation of these provinces. Most of them (29 installations) are located in West Pomeranian Province, while only 17 emitters in Lubusz Province. They generated 10 390 371 Mg of CO_2 in 2014 with a huge gap between the average and the median emissions (uneven emission distribution).

Table 5

Descriptive statistics of CO_2 emission [Mg] in Lubusz and West Pomeranian Provinces

Mean	225 877.63
Median	46 106.00
Minimum	10 634.00
Maximum	4 651 831.00
Sum	10 390 371.00
Count	46

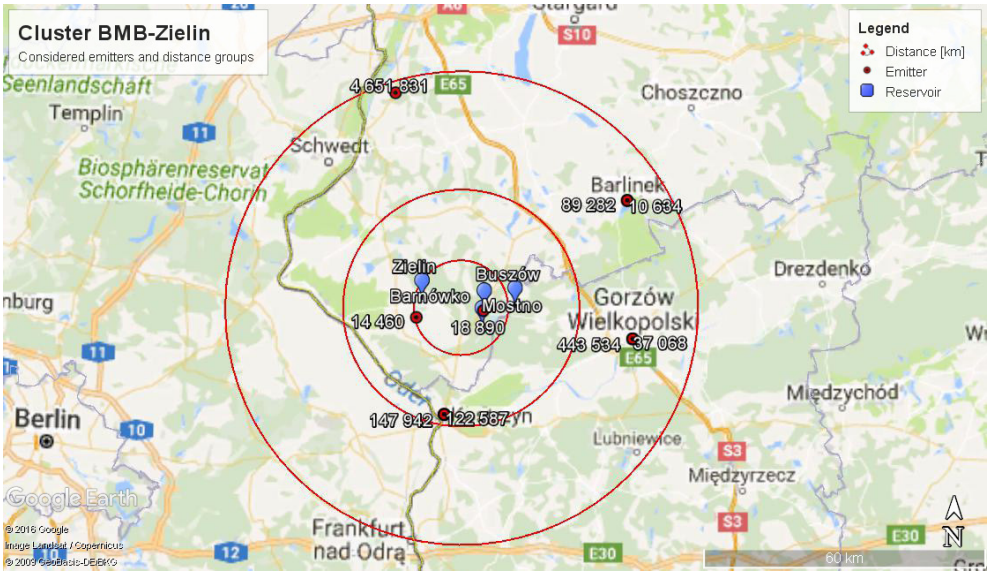

Fig. 8. Location of the most significant emitters for the BMB–Zielin cluster

Source: Institute of Environmental Protection data, Google Earth

There are 10 companies in the area to 50 km from the cluster center (Fig. 7), which additionally generated 5 579 351 Mg of CO_2 per year. Most of the analyzed emitters (9 installations) are related to the energy sector and produced 5 536 228 Mg of CO_2. While, only one company generating 43 123 Mg of CO_2 is used to the paper and wood manufacturing. At the Figure 8 there is presented the location of the most significant emitters for the BMB–Zielin cluster.

There are only 2 emitters from the energy sector in the nearest area (to 10 km), whose annual emissions amounted to 14 460 Mg of CO_2 (Troszyn) and 18 890 Mg of CO_2 (Barnówko). However, there are three emitters located from 10 km to 25 km from the cluster center, all in Kostrzyn nad Odrą. Two emitters from the analyzed region are related to the energy sector (270 529 Mg of CO_2), while only one company is connected with the paper and wood manufacturing (43 123 Mg of CO_2). Moreover, the annular space with the radius from 25 km to 50 km from the cluster center includes 5 companies related to the energy sector. Two of them are located in Gorzów Wielkopolski, two in Barlinek and one in Nowe Czarnowo. The largest emitter from this region generated in 2014 tremendous amount of carbon dioxide equal to 4 651 831 Mg, which affected the total region emission (5 232 349 Mg of CO_2).

Many factors were taken into consideration and as the result three emitters were finally selected (Fig. 9). All of them are related to the energy sector and use installations to the fuel combustion process. The smallest emitter is also the farthest one because it is located in Barlinek (41,9 km from the cluster center) and generated 89 282 Mg of carbon dioxide. Emitter producing 443 534 Mg of CO_2 per year is located in Gorzów Wielkopolski, while the company with annual emission equal to 147 942 Mg of CO_2 is situated in Kostrzyn nad Odrą.

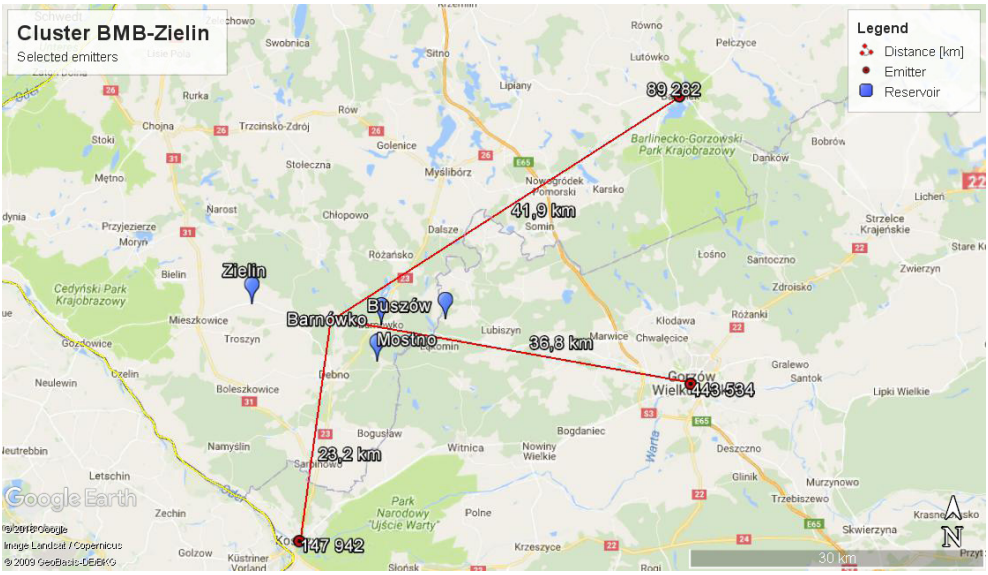

Fig. 9. Location of the selected emitters for the BMB–Zielin cluster

Source: Institute of Environmental Protection data, Google Earth

3. SUMMARY

The comprehensive selection process of emitters which are suitable for being suppliers of carbon dioxide for the clusters considered in the project MUSE was carried out. Firstly, installations with annual emission not lower than 10 000 Mg of carbon dioxide per year (database made in 2014) were chosen. Then, detailed statistical analysis of emitters located in provinces surrounding Roztoki–Jaszczew–Potok, Pławowice–Grobla, Lubiatów–Międzychód–Grotów, BMB–Zielin clusters was conducted. Next stage of selection was connected with reduction of emitters number to these located closer than 50 km from the clusters centers and with their detailed analysis. After that, factors such as their emission and its character, installation type, kind of the company and distance from the cluster were taken into account to finally select potential suppliers of carbon dioxide for four considered clusters.

After detailed analysis, two emitters were finally selected for the Roztoki–Jaszczew–Potok cluster. First one is located in Jasło and generated 63 973 Mg of CO_2 per year (chemical industry), while the second one from Krosno produced 43 866 Mg of CO_2 connected with the mineral industry.

The emitters selection for the Pławowice–Grobla cluster finished with three companies. The emitter from Tarnów includes one installation connected with the energy sector (806 969 Mg CO_2) and one with the chemical industry (333 351 Mg of CO_2). Two other emitters are also related to the energy sector. The company from Kraków produced 1 864 996 Mg of CO_2, while this from Skawina emitted 1 516 040 Mg of carbon dioxide in 2014.

In the case of the Lubiatów–Międzychód–Grotów cluster two emitters were finally selected. First one is situated in Sieraków and generated 69 441 Mg of CO_2 (mineral industry). The next one with annual emission of 58 239 Mg of CO_2 (energy sector) is placed in the area of Lubiatów reservoir.

The selection of the carbon dioxide suppliers for the BMB-Zielin cluster finished with three emitters related to the energy sector. The smallest producer (89 282 Mg of CO_2) is located in Barlinek. Another one, which produced 443 534 Mg of CO_2 is located in Gorzów Wielkopolski, while the company with annual emission equal to 147 942 Mg of carbon dioxide is situated in Kostrzyn nad Odrą.

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