Article

External Costs for Agriculture from Lignite Extraction from the Złoczew Deposit

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Abstract: In many circles, including in Poland, lignite is still viewed as a cheap source of energy, which is only possible if the external costs associated with mining and burning coal are not taken into account. In Poland, this is reflected in plans to open new Złoczew opencast lignite mines. In previous studies, the analysis of external costs has focused on the external costs of coal combustion and related pollutant emissions. This paper focuses on the extraction phase. The aim of the work here described was to estimate the external costs that agriculture may incur due to the formation of a depression funnel for the projected lignite mine in the Złoczew deposit. This paper discusses factors causing uncertainty in calculated estimates of external costs in agriculture, and characterizes the Bełchatów and Złoczew opencast mines. In the paper, a methodology for calculating external costs in livestock production is then proposed. In the next part of the study, the decrease in cereal and potato yields and in the number of cattle and pigs in the area of the cone of depression of the Bełchatów opencast mine, which has been in operation for 40 years, were estimated. The estimates obtained formed the basis for estimating external costs for the planned Złoczew lignite opencast. The analyses showed high external costs for plant production and much lower for animal production. The inclusion of the estimated external costs of $12.2 \text{ €} \times \text{kWh}^{-1}$ in the costs of electricity production will significantly worsen the profitability of launching this opencast. The paper discusses factors causing uncertainty in calculated estimates of external costs in agriculture, and characterizes the Bełchatów and Złoczew opencast mines. The discussion also shows that the level of losses incurred in crop production due to opencast coal mining is similar to the losses incurred in crop production in extremely dry years.

Keywords: external cost; opencast lignite; plant production; animal production; depression funnel

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1. Introduction

Poland is a country with large lignite resources. At the end of 2014, the total geological balance resources of lignite, located in 90 deposits throughout Poland, amounted to 23.5 billion Mg, of which nearly 1.5 billion Mg has already been developed [1]. Currently, the annual mining of over 60 million Mg is carried out in six opencast mines in three lignite areas. The extracted lignite generates electricity, which satisfies approximately 30–35% of Poland's demand. If new opencast mines are not put into operation, coal mining of more than 50 million Mg will continue only until 2030. By 2036, it would decrease to less than 20 million Mg, to cease around 2045 [2]. Energy companies are currently working on putting more lignite deposits into operation in Poland. To date, the most advanced mining works are performed in Złoczew and Ościsłowo deposits. In the case of the Złoczew deposit, with 611 million Mg of resources, a decision on environmental conditions for the proposed opencast mine was issued on 28 March 2018. The only requirement that is missing to launch the opencast mine is the exploitation concession [3]. For the second deposit, the implementation of the investment project was suspended due to the lack of a decision concerning environmental conditions that have to occur for the opencast mine to operate. The demands of the energy sector are partially reflected in the Energy Policy of Poland until 2040 [4], approved in February 2021, which provides for the possibility

of initiating lignite mining in two new deposits, Złoczew and Ościsłowo. The strategy leaves the final decision on launching such exploitation to investors, indicating the key role of the price of CO₂ emission rights, environmental conditions, and development of new technologies. However, the said document does not mention the external costs associated with the potential exploitation of these deposits.

New mining and energy projects are being implemented in numerous developing countries with large coal reserves, such as China, India, Turkey, Vietnam, Indonesia, Bangladesh, Japan, South Africa, and the Philippines [5,6]. On one hand, their implementation is motivated by a rapidly growing demand for electricity while on the other, by very high security of supply, which no other mined energy source can match [7]. The continuously popular opinion that lignite is the cheapest or one of the cheapest sources of energy, is also crucially important [8–11]. This applies to Poland as well [12–15]. However, such a perception of lignite is only possible if external costs associated with mining and burning coal are not taken into account. They also point out that, in view of the lack of large reserves of other energy resources, further coal mining in Poland is necessary to ensure energy security [12–15].

There are many definitions of external costs. In the case of electricity production, they indicate costs incurred in connection with the production of electricity by third parties and future generations, rather than the expenditures of direct recipients and providers of electricity [16,17]. In contrast, the external cost, understood as the monetary value of the damage caused by electricity production, is today the most widely accepted common denominator for valuing environmental impacts [18–20].

Such costs are associated with coal burning and the resulting air pollution, which affects climate change (e.g., through CO₂ emissions) and human health by increasing the number of respiratory, vascular and other diseases, premature deaths, medical costs and days of medical leave, as well as reducing the productivity of the economy. Furthermore, opencast coal mining entails costs incurred by the environment, in particular related to the deterioration of the surface and underground water quality and the occurrence of a depression cone, which causes losses in agricultural and forestry production, as well as leading to surface deformation, increased dustiness, noise, etc. The environment also bears significant costs through depletion of biodiversity, elimination or obstruction of functioning of ecological corridors, as well as the loss or reduction of natural and tourist values in large areas [21,22]. Their valuation is necessary to render the costs of electricity production real, thanks to which, the undertaken decision will be as close as possible to the ecological, economic, and social optima.

Tol's review of the literature on damage caused by climate change, which includes over 588 estimates from 75 published studies, indicates that the problem of external costs associated with CO₂ emissions into the atmosphere is widely recognized [23]. Numerous studies have also been undertaken to value the costs arising in connection with deterioration of human health caused by emissions from burning coal [16,22,24–27]. The literature estimating the external costs associated with opencast coal mining is much poorer [28]. Authors of one of the few studies in this area analyzed the impact of particulate matter emissions from lignite mining performed in the South Field Mine of the Lignite Center Ptolemais-Amyntaion located in Greece [28]. A team led by Pepliński have undertaken another research project, which focused on studying the effects of a depression cone created as a result of the opencast lignite mining in Poland on agricultural production. During the initial works [29–31], the authors assumed numerous simplifications regarding the level of decrease in crops and livestock, e.g., an identical level of decrease in crops and livestock throughout the entire period of studies concerning the influence of opencast mines. It was calculated by comparing the crop level from the region of the Konin lignite field (located in the eastern part of Wielkopolskie Voivodship in Poland) with the referential crop level (i.e., from the rest of the said voivodship) before launching the opencast mines and 30 years later, which raises the risk of significant overestimation or underestimation of external costs for the intermediate periods. A subsequent paper undertook a more detailed study

on the decline in the level of crops in this region [32]. However, to our knowledge there have been no studies that analyze the impact of opencast lignite mining on the level of animal production.

In connection with plans to launch the Złoczew opencast mine, it is necessary to estimate the actual costs of electricity production using coal from this deposit, including the external costs. The following study aimed to estimate the external costs associated with the exploitation of lignite in agriculture, both in plant and animal production, for the projected Złoczew opencast mine, which will complement the knowledge of the actual costs of electricity production from lignite.

2. External Costs in Agriculture and Difficulties Associated with Their Estimation

In agriculture, external costs are connected with depression cones found around the opencast lignite and other resource mines. Their formation is linked with the deposit drainage, which must be carried out to the depth at which the raw materials are mined. In the case of lignite, it is usually a range between tens and over 200 m b.g.l. There are two types of depression cones: discharge and pressure relief. The former is created due to the gravitational flow of water towards the drained deposit. This results in the creation of a depression cone, which in the vertical section is a cone-shaped curve, i.e., the water table at the edge of the opencast mine rises quickly, but as the distance increases, the water table rises at a slower pace. The Polish law obliges the investor to define the estimated area around the opencast mine where the water table will be permanently lowered by at least one meter, creating an area of depression cone. In the case of lignite opencast mines, the range of the depression cone usually varies between a few to several kilometers, starting from the edge of the opencast, and has the shape of an ellipse. However, in the case of agriculture, for which groundwater is particularly important in plant production, the impact area extends far beyond the area of the established depression cone and reaches up to several dozen kilometers from the edge of the opencast.

In turn, the pressure relief cone, which is much larger than the depression cone area, is the territory where groundwater pressure is reduced. A change in water pressure in deeper aquifers caused by hydrogeological windows can lower the groundwater and surface water levels, as it triggers a local outflow of water to deeper ground layers. It can also reduce or generate a decline in subsoil resource supply system, which uses water from deeper aquifers [32–34].

Difficulties in estimating production losses and assessing the external costs in crop production result from numerous interrelating factors. These include geological, natural and climatic, agricultural and production, as well as temporal and spatial factors.

The key geological factors include:

- Dewatering depth and time;
- The location of the opencast in the catchment area, the size of the catchment area and directions of the groundwater flow;
- Geological structure of drained areas;
- The size of supply with rainwater and surface water; and
- The initial (primary) level of groundwater, which in the case of peripheral areas of the impact zone indicates that the mine would affect areas with higher water levels and would have no influence on the surrounding areas with lower water tables, even those located further away.

In terms of natural and climatic conditions, the intensity of precipitation and its distribution during the growing season are particularly important in the context of the topic under discussion.

Agricultural and production difficulties are linked to the biological nature of production. The crop levels obtained by farmers depend, among other things, on natural factors, such as type, quality and pH level of soil, topography, length of the growing season, precipitation, temperature, and water table. There are also economic factors which include, e.g., the level of agricultural development, agrarian structure, production intensity, availability

of techniques and technologies, and quality of human capital. A broader description of difficulties arising in connection with estimating production losses in crop production in the area of influence of opencast mines was presented by Pepliński and Czubak [32].

The launch of an opencast mine disrupts the existing production conditions. However, their importance varies in particular areas around the opencast due to the factors described above. Such influence would also differ in opencast mines located in different regions of a country, continent, or other areas of the world, rendering it impossible to fully apply the results of the observation from one object to another.

Many factors determine the level of impact of opencast mines on the amount of livestock, also in the case of animal production. Their direct influence is restricted to the elimination of livestock herds (or flocks) from farms located above the deposit and the area of associated infrastructure. Farms located in the vicinity of an opencast may also cease or reduce their production and subsequently lose all or part of their agricultural land, which constitutes their primary feed base. The indirect influence of opencast mines is associated with a decrease in livestock due to a decline in feed production, which in turn results from a drop in feed crops occurring in the area of a depression cone. The decrease in livestock in the depression cone area is influenced, i.e., by:

- The level of crop decline—in the case of farms located in the vicinity of an opencast, the rate of livestock decline would be higher than in regions located further away from the edge of the opencast, although it is difficult to establish the limit of crop decline that would not translate into a decline in livestock;
- Animal species—the most sensitive are ruminants, i.e., cattle and sheep that require large quantities of roughage, such as green fodder, haylage, silage and hay, which are usually produced on the farm itself or in the immediate vicinity. Due to their high economic sensitivity to transport, the possibilities of long-distance transit are limited. In the case of roughage stored in silos, its daily delivery also constitutes a restriction due to the rapid rate of feed spoilage. Pig farming is less sensitive to a decrease in feed production. In Poland, the share of own feed in pig farming reaches approx. 50% [31]. In contrast, poultry production, which relies almost entirely on industrial feed, is independent of its own feed;
- Production scale—smaller farms are more sensitive to decreases in production on their farm, as they cannot rely on discounts due to the purchase of small quantities of feed. Over time, smaller farms are more likely to cease animal production. Development of animal production is also inhibited since the increase in costs of producing own feed reduces the yield of the entire farm, thus decreasing the number of funds allocated for investment projects and development. In the case of farms operating on a large scale, emerging feed shortages are supplemented with purchased feed. In ruminant farming, it is common to purchase or lease additional land, which further inhibits the growth of these units in the long-term perspective;
- The level of production yield in the long term, which determines the economic condition of agriculture. At low profitability of animal production, the additional reduction in profit resulting from the loss of a part of own feed increases the propensity to cease a given production and the tendency to take over farms by successors;
- The level of agricultural development, including the level of plant production, the acquired expertise, wealth, and the degree of cooperation between local agriculture and the environment;
- Time of occurrence of the depression cone, since the economic conditions for agriculture in the impact area deteriorates as the period of the opencast mine's operation lengthens. This would be expressed by the reduction of investment projects and the purchase of modern technologies.

Such a large number of factors, together with the difficulty in estimating the impact of the depression cone and the associated decrease in the amount of own feed on the level of animal production, indicate that the obtained results would be characterized by a certain level of underestimation or overestimation. However, uncertainty is a well-known

phenomenon associated with the estimation of external costs of electricity production, as it is better to acquire even an estimated assessment of external effects rather than completely disregard or ignore such influence. Furthermore, despite the uncertain results, they allow drawing sensible conclusions [24]. Further research may expand the knowledge and reduce the level of uncertainty, thus validating the performance of subsequent studies concerning all external costs associated with electricity production.

3. Characteristics of Bełchatów and Żłoczew Opencast Mines

Since the process of coal mining from the Żłoczew deposit is still in the planning phase, estimation of losses in agricultural production must be conducted based on data from an already existing opencast mine that is characterized by similar parameters in terms of the size and depth of the lignite deposit. In the case of the Żłoczew deposit, these criteria are best met by the Bełchatów deposit.

The Bełchatów deposit is one of the largest opencast lignite mines in the world. The maximum depth from which coal is extracted reaches an average of 280 m b.g.l., which indicates that the original groundwater table in the mining area is lowered by an average of 280 m, but 352 m at the maximum (Table 1). Dewatering of the Bełchatów deposit began in the second half of 1975, while mining launched at the end of 1980. Originally, the plans involved exploitation of the Bełchatów field until 2020, but this term was extended until 2026 to extract small amounts of coal from the sidewalls of the excavation. In turn, it is expected that the Szczerców field will be mined until around 2038. Total resources of this deposit were estimated at 1.8 billion Mg, of which approximately 1.1 billion Mg were located in the Bełchatów field, while 720 million Mg were in the Szczerców field. By the end of 2017, 1169 Mg of coal had been mined while 618 Mg remained to be extracted [12,35]. It was necessary to remove more than 4510 million m³ of overburden, of which 1400 million m³ formed Kamieńsk Hill, which has an elevation of 195 m and is located next to the Bełchatów field, and a spoil tip located next to the Szczerców field, which has an elevation of 170 m and consists of 1100 million m³ of the overburden. They occupy a total of 2640 ha and are currently being reclaimed for forestry and recreation [12,36,37].

Table 1. Parameters of the geological location of the coal seam(s) in individual deposits.

Deposit Name	Overburden Thickness (m)			Coal Thickness (m)			Depth of the Deposit Floor (m b.g.l.)		
	Min.	Average	Max.	Min.	Average	Max.	Min.	Average	Max.
Bełchatów—Bełchatów field	0.0	24.3	158.8	3.0	55.1	230.5	3.0	79.5	245.5
Bełchatów—Szczerców field	7.6	119.5	239.8	8.9	50.3	196.1	65	171.1	351.7
Żłoczew	138.4	215.1	280.9	12.1	51.4	127.8	150.5	266.6	354.3

Source: Based on [35].

Since the beginning of the opencast mine's operation, 9.3 billion m³ of water have been pumped out. As a result, the average waterlogging index amounts to 7.96 m³ × Mg^{−1}, while the average for the entire Polish lignite mining industry is 6.8 m³ × Mg^{−1}. In 2017 alone, 200 million m³ of water was pumped out, which gave the waterlogging index of 4.71 m³ × Mg^{−1} [12]. The area of the depression cone is subjected to continuous changes along with the progress of mining and dewatering depth, as well as depending on the amount of precipitation. Between 1976 and 2004, the average area of the groundwater depression cone was 438 km², with a maximum area of 635 km² in 1992. The depression cone was shaped similarly to an ellipse, measuring 40 km (W-E axis) and 20 km (S-N axis). After launching the dewatering process in the Szczerców field in 2000, the depression cone rapidly expanded towards the west, which increased the dimensions of the depression area to 45 km and 25 km, while the maximum area amounted to approx. 800 km² [35,38,39]. The investigation also revealed numerous areas of lowered groundwater levels outside of the main depression cone area, indicating the presence of multiple hydrological windows. They cause groundwater outflows into the deeper layers due to a decrease in water pressure (pressure relief cone) located below the discharge cone [40].

Reclamation plans provide for the creation of a lake, with a maximum depth of approx. 100 m, over an area of about 3250 ha located in the final excavations of both fields. Its filling is expected to take place over a period of 20 years and be completed around 2070. The remaining land will be reclaimed and used primarily for forestry and, to a lesser extent, recreation and industry [41]. It is estimated that in the absence of an additional supply, the restoration of water relations around the Bełchatów mine will be completed by 2110. With the use of an additional external water supply system, this time may be shortened by 15 years. It would require additional 60 years to achieve the steady-state conditions, i.e., invariability of the water flow over time [39,42].

The Złoczew deposit is located approximately 50 km (in a straight line) from the Bełchatów deposit and stretches from south-west to north-east, in the form of a narrow, 1000–1500 m wide strip for about 10 km. To accommodate an opencast mine, an external spoil tip and the necessary infrastructure, it will be necessary to occupy approx. 6100 ha of land [43]. The coal is deposited at a depth of about 300 m, while the maximum exploitation depth will amount to approx. 354 m b.g.l. It is expected that this deposit will allow 485.8 Mg of lignite to be extracted over 31 years, with a maximum annual extraction of 18 million Mg. Significant depth of the deposit and the long mining period will contribute to the creation of a depression cone over a large area. However, there are considerable discrepancies in this regard. According to the authors of the 2017 report on the environmental impact, commissioned by the investor, the maximum reach of the discharge cone would amount to 311.53 km² [44]. In turn, other authors estimate the maximum reach of the said discharge cone to be 14–16 km from the center of the mine at the moment of its full expansion, i.e., 615–803 km², which is a cone area similar to the size of the Bełchatów opencast [35,45]. In extreme cases, it may even reach 3100 km² [43]. Although the lignite in the Złoczew deposit, similarly to that in the Bełchatów deposit, is located in a rift valley, in Jurassic and Cretaceous formations filled with Miocene and Quaternary formations it is characterized by significantly different factors influencing the extent of the depression cone. Contrary to the Bełchatów deposit, in the case of the Złoczew deposit, attention should be focused primarily on the predominance of water-bearing formations (sand and gravel) over impermeable formations (clays and loams) in the vertical profile, which has numerous hydrogeological windows, and common, strong fractures with developed karstic features and faults conducive to the shaping of a depression cone in the Jurassic aquifer (Figure 1) [43,45,46]. Hydrogeological windows would also account for local declines in groundwater levels outside the area of the designated depression cone due to decreases in water pressure in deeper soil layers.

Within 6.5 years of accessing the deposit [47] and 31 years of exploitation, about 6300 m³ of water will be pumped out, which, with the extraction of 485 million Mg of coal, gives a waterlogging index of 13.1 m³ × Mg^{−1}, i.e., more than a half higher than in the Bełchatów deposit [45]. After the coal extraction, the initial plans provided for the creation of a water reservoir on an area of 2345 ha, located in the place of the final excavation, in the eastern part of the opencast mine. The reservoir's filling would be supported by water from Warta and Oleśnica rivers extracted during the periods of increased water flow, which is expected to take place within 16 years [44].

For most opencast mines, it is estimated that after dewatering the deposit, water relations will normalize in an amount of time that is approximately equal to the dewatering period. In the case of the deposit in Bełchatów, the dewatering period is expected to last about 73 years while the restoration of water relations is planned to be completed after 72 years, provided that the final reservoir is filled naturally. A higher waterlogging index of the Złoczew deposit indicates that the said process may take longer than 38 years, particularly since this is a region of low rainfall, snowless winters, and long-lasting droughts.

Figure 1. Geological cross sections through the Złoczew lignite deposit. Source: Based on [46].

The high complexity of the processes and the desire to obtain reliable loss estimation resulted in the adoption of fairly conservative assumptions that the impact area of the Złoczew opencast would be similar to that of the Bełchatów opencast and the period during which the Złoczew opencast will influence the surrounding area would be 76 years, including 38 years of dewatering and further 38 years of restoring water relations.

4. Materials and Methods

To estimate the external costs associated with the planned launch of the Złoczew deposit that are borne by agriculture, it is necessary to estimate the potential losses in plant and animal production, which result from:

- Occupying the area of agricultural land by the opencast, the external spoil tip and the necessary infrastructure, e.g., power plant, conveyor belts, access roads, etc., which in further parts of this paper will be referred to as the “opencast area”; and
- The presence of areas with lowered groundwater level (also those lowered by less than 1.0 m), which in further parts of this paper will be referred to as “the depression cone area” or “area of influence of the opencast”.

In the case of plant production, crops of cereals and potatoes were analyzed, which was dictated by the availability of data on crops and agricultural acreage regarding the entire period under review. In turn, the sugar beet harvest was not analyzed, as in the area influenced by the Bełchatów opencast the cultivation of sugar beet has a marginal significance—e.g., in the (former) Piotrków Voivodship, it did not exceed 50 ha in several

years of the analyzed period. In the case of animal production, the following types of livestock were analyzed: cattle, cows, pigs, and sows, i.e., groups of animals, whose feeding, in Polish conditions, is based primarily on the feed produced on the farm. Since the Złoczew deposit is in the planning phase, the level of production losses was estimated based on the changes in crops of the aforementioned plants and changes in selected types of livestock in the area of influence of the Bełchatów deposit. Since the period of influence of the Bełchatów opencast on the surroundings, including agriculture, is longer than the one of the Złoczew deposit, the analysis included losses in agricultural production covering a period of 38 years from the launch of dewatering of the Bełchatów opencast, i.e., from 1975 to 2013. The time necessary for the water relations to restore would cause the disappearance of the depression cone at a rate corresponding to its formation. Therefore, it was assumed that the losses in agricultural production, which occurred in particular years of the period required for water relations to normalize, would correspond to the losses from the opencast mining period in reverse order, i.e., from the last to the first year of exploitation.

Analyses estimating losses in agricultural production included data from a series of statistical yearbooks prepared by Statistics Poland, such as the Statistical Yearbook of Voivodships, the Yearbook, the Statistical Yearbook of Regions, statistical yearbooks of individual voivodships, and others [48–58].

Due to the level of detail of the available data and the administrative reforms implemented in Poland, the analysis was carried out using a multivariate approach. The basic analysis was conducted at the level of voivodships, in accordance with the administrative division effective in 1975–1998, which distinguished 49 Polish voivodships. The assessment of losses in crops and livestock occurring in the area affected by the Bełchatów opencast was based on three groups of voivodships:

- Group I, which included only the Piotrków Voivodship, where the Bełchatów lignite opencast mine is located;
- Group II, which included Sieradz and Częstochowa voivodships, located in the nearest vicinity of the opencast mines; and
- Group III, which included another six voivodships, located at an average distance of up to 100 km from the Bełchatów opencast, i.e., Kalisz, Kielce, Opole, Płock, Radom, and Skierniewice voivodships. This area will also be referred to as the reference area.

In the case of plant production, the analysis included the period until 1997 due to the fact that, from 1998 onwards, data on crops are available only according to the new administrative division, which distinguishes 16 voivodships. Such an administrative division renders it impossible to assess the impact of the Bełchatów opencast on agriculture. Therefore, an additional analysis, comparing the crop level decrease rate in areas influenced by the Bełchatów opencast with the crop level decrease rate in areas affected by opencast mines located in the Konin lignite field, was conducted and subsequently published by Pepliński and Czuba [32]. The analysis of changes in crop levels was conducted using five-year averages, thus reducing the level of crop variability resulting from weather conditions.

Regarding animal production, data on livestock are available at a district level, covering 1973, 1996, 2002, and 2010. Such data were used to calculate the number of analyzed animal species in areas corresponding to the area of voivodships distinguished according to the 1975–1998 division.

Moreover, only in the case of animal production, an analysis of changes in the head of cattle (without cows), cows, pigs (without sows), and sows around the Bełchatów opencast mine was conducted at a district level, in which 5 sectors were distinguished:

- The first sector, marked as “up to 20 km”, includes the district of Bełchatów, in which the Bełchatów opencast mine is located;
- The second sector includes two districts located at an average distance of 21–40 km away from the opencast mines;
- The third sector includes five districts located at an average distance of 41–60 km away from the opencast mines;

- The fourth sector includes five districts located at an average distance of 61–80 km away from opencast mines; and
- The fifth sector includes twelve districts located at an average distance of 81–100 km from the opencast mines and constitutes the reference area for the other sectors.

Taking into consideration the assumption that the area of influence of the planned Złoczew opencast will be similar to the area of influence of the Bełchatów deposit, it is also necessary to define “Area I” and “Area II” for the Złoczew deposit. It was established that “Area I” covers the whole of the Sieradz Voivodship, where the planned Złoczew opencast is located, and 9.7% of Kalisz and Częstochowa voivodships, which in total corresponds to the area of the Piotrków Voivodship, where the Bełchatów deposit is located. The area of Kalisz, Częstochowa, Opole, and Piotrków voivodships, which corresponds to the area of voivodships from Group II for the Bełchatów opencast, was defined as “Area II”. The area of five district sectors around the Złoczew opencast was determined according to similar principles.

With regard to external costs of plant production, arising in connection with the opencast lignite mining in the Bełchatów deposit, the study adopted the methodology developed by Pepliński and Czubak [32]. In the following study, external costs were calculated by distinguishing two depression cone areas (Ad_{AL}), i.e., “Area I” corresponding to the amount of agricultural land in voivodships from Group I, and “Area II” corresponding to the amount of agricultural land in voivodships from Group II.

In the case of animal production, the plan provides for the performance of an analysis comparing changes in the head of cattle, cows, pigs, and sows with the said livestock converted to a large size unit (LSU) at voivodship and district levels. The LSU is a unit of 500 kg. The conversion was based on indicators used by Eurostat [59]. The estimated losses, expressed as the LSU, will be subsequently used to calculate the external costs for each animal group. The decrease in livestock, which resulted from the launch of the Bełchatów opencast, was calculated for individual years based on the following formula:

$$SL_i = 100 - \frac{100 + LSUd_i}{100 + LSU_i} * 100 \quad (1)$$

where SL_i —the estimated loss level (%), $LSUd_i$ —the change in the head of cattle (excluding cows), cows, pigs (excluding sows) and sows occurring in the examined area of impact of the opencast in the i -th year, compared to the base year, i.e., 1975, expressed as the LSU (%). In the paper, losses occurring in “Area I” and “Area II” and sectors 1–4 will be estimated separately, LSU_i —the change in the head of cattle (excluding cows), cows, pigs (excluding sows), and sows occurring in the designated reference area, i.e., “Area III” and sector 5 in the i -th year, compared to the base year, i.e., 1975, expressed as the LSU (%).

External costs in animal production in the depression cone area were calculated according to the following formula:

$$Ec_{zf} = \sum_{i=1}^n S_i \frac{SL_i}{100} * Pr_i * t * p_i * P_i \quad (2)$$

where Ec_{zf} —external costs in animal production, S_i —the average livestock level of the i -th group of animals in the analyzed area (number of animals), SL_i —the estimated average level of livestock losses over the entire period of impact of the opencast mine (%), Pr_i —annual productivity of a given group of animals (kg of beef/pork per animal, litres of milk per cow, piglets per sow), t —time of influence of the opencast mine (years), p_i —the average selling price of an animal product (e.g., USD, EUR $\times$ kg⁻¹). P_i —yield of production concerning the i -th group of animals (%). Regarding the calculations, it is also possible to adopt equal levels of yield for all animal production.

In the case of production losses occurring in the area occupied by the opencast mine, the external spoil tip and the necessary coexisting infrastructure, e.g., a power plant,

conveyor belts, access roads, etc., together forming the external costs (Ec_{zo}), were calculated according to the following formula:

$$Ec_{zo} = \sum_{i=1}^n S_i * Pr_i * t * p_i * P_i \quad (3)$$

The estimation of external costs associated with the possible launch of the Złoczew opencast mine for agriculture was based on the most recent statistical data from Statistics Poland [57]. In the calculations, the study assumed:

- The average sowing structure from the 2015–2019 period for the analyzed areas;
- The acreage of the agricultural land from 2019, including subsequent changes in agricultural land acreage from the 2010–2019 period;
- Average selling prices for plant and animal products from the 2015–2019 period;
- The average yield for plant and animal production at identical, 25% level [31];
- Three variants of changes in crop levels. Variant I assumed the average level of cereal and potato crops from the 2015–2019 period. In Variant II, the crop level from the 2015–2019 period was subsequently adjusted to include trends in productivity changes occurring in the area of influence of the Złoczew opencast mine between 1981 and 2019. In turn, Variant III includes the rate of crop increase based on the rate of crop changes occurring in the two most agriculturally important German states, North Rhine-Westphalia and Lower Saxony between 1981 and 2019 [60]. Due to a large increase in crops between 1981 and 2019, it was also assumed that between the 39th and the 76th year since the launch of the Złoczew opencast, the level of crops would not change in Variant II and Variant III, remaining at the level of productivity estimated for the 39th year after the launch of the opencast;
- Three variants of changes in the population of cattle (excluding cows), cows, pigs (excluding sows) and sows and their productivity. Variant I—the animal population and productivity from 2019 was adopted, Variant II—the animal population and productivity from 2019 were adjusted according to the average pace of changes in the number of animals and productivity in the period from 2010 to 2019. Variant III—an average pace of changes in the animal population and productivity in North Rhine-Westphalia and Lower Saxony from 1981 to 2019 was adopted [60];
- The average rate of exclusion of the land for the exploitation of Złoczew opencast mine during the operation period of 60% [30,61]. Since non-agricultural reclamation of the area is planned for the region of Bełchatów [62], a similar method of reclamation of Złoczew opencast mine is also adopted. Therefore, the average shutdown rate of the opencast mine in Złoczew over 76 years is going to be 80%.

Kruskal-Wallis one-way analysis of variance by ranks test was used to test the homogeneity of the distributions of yield change dynamics in the studied regions. This test was used to verify the hypothesis that the differences between the medians of the study variable were not significant in several populations.

The hypothesis concerns medians of consecutive populations:

$$H_0: \Theta_1 = \Theta_2 = \dots = \Theta_k$$

$$H_1: \exists i, j \in \{1, \dots, k\} \Theta_i \neq \Theta_j$$

where $\Theta_1, \Theta_2, \dots, \Theta_k$ is the median of the tested variable x for the i -th group.

Hypothesis verification was based on a statistic defined by the formula:

$$H = \frac{1}{C} \left(\frac{12}{n(n+1)} \sum_{i=1}^k \frac{T_i^2}{n_i} - 3(n+1) \right) \quad (4)$$

where $n = n_1 + n_2 + \dots + n_k$; T_i ($i=1, 2, \dots, k$) denotes the sum of ranks in each trial; C —correction for bind ranks $C = 1 - \frac{\sum (k^3 - k)}{n^3 - n}$.

The p value determined on the basis of the test statistic was compared with the significance level α :

if $p \leq \alpha \Rightarrow$ we reject H_0 and accept H_1

if $p > \alpha \Rightarrow$ there are no grounds to reject H_0

In assessing yield level differences between starting years (1956–1960) and final years (1993–1997), analysis of variance (ANOVA) was also used to show statistically significant differences between the means in the three groups identified. In the analysis of variance, groups of n_i elements were compared, yielding a total of $n = \sum_{i=1}^k n_i$ independent observations x_{ij} for $j = 1, 2, \dots, n_i$ [63]. The presence of differences between the means indicated an association between the mean for the tested observation and the qualitative variable that was the basis for separating the groups (here: distance from the outcrop). The null hypothesis of equality of all group means $\mu (1, 2, \dots, i)$ was tested:

$$H_0: \mu_1 = \mu_2 = \mu_3 = \dots = \mu_k$$

where $\mu_{(1, 2, \dots, k)}$ denotes the mean of the dependent variable in the k -th group, towards the alternative hypothesis:

H_1 : at least two group means differ.

In view of this, the alternative hypothesis was that there was a significant difference between the compared groups means.

The decision to accept or reject the null hypothesis was based on the Fisher-Snedecor F test determined as:

$$F = \frac{\text{intergroup variance}}{\text{intragroup variance}} \quad (5)$$

If the analyzed factor of group separation is significant, then the variation within each separated group will be small (the intragroup variance will be small). The greater the difference between the groups (the intergroup variance) and the smaller the difference between the elements of each group (the intragroup variance), the larger the value of the F statistic, which argues against the null hypothesis of equality of means in the compared groups, and therefore is the basis for the rejection of H_0 . The presence of statistically significant differences in yields was verified using the analysis of variance at the significance level of $\alpha = 0.05$ [63].

The lignite deposits in Złoczew will be used in the Bełchatów power plant. Currently, there are 12 power units in operation, 11 out of which of a capacity of 370–390 MW and gross efficiency after modernization of approximately 38.5% with a net efficiency of approximately 36.0% were put into service in the period from 1981 to 1988. The last unit, of a capacity of 858 MW, was commissioned in 2011 and its gross efficiency was 44.4%, while net efficiency was 41.3% [64]. In 2018, in the power plant in Bełchatów, 1.355 Mg of lignite was used to produce 1 MWh of net electricity [65]. Assuming that the efficiency of the coal extracted from the deposits in Złoczew, as a result of the modernization of the units, is going to be approximately 10% more and that the least efficient units are going to be shut down, the average consumption of lignite will be approximately 1220 Mg. There will be approximately 398.2 TWh of net electricity generated.

5. Results

Agriculture in Poland is characterized by a low level of concentration, which is reflected by a small acreage of an average farm and a low average number of farm animals in farms that run livestock production. It is also characterized by low productivity, including low yield and low animal production. The pace of improvement of productivity of Polish farming and the concentration processes are still too slow to achieve the level of development of Western European countries [66–68]. Agriculture in the areas affected by the extraction of coal deposits in Bełchatów and Złoczew is characterized by smaller farms compared to other parts of Poland—25% smaller on average, and a slower than average

growth rate of the size of farms. The milk yield of dairy cows and the fertility of sows are also slightly lower [58,68].

Construction of the opencast mine in Bełchatów and the formation of the depression cone had a negative effect on the level of cereal and potato yield and, out of all plants analyzed, the highest increase of the yield was observed in the voivodships of Group III, i.e., the areas not affected by the operation of lignite opencast mines (Table 2). The results obtained that show the lowest increase in the yield in the voivodships of Group II might be a consequence of poor data received from Sieradz Voivodship, where the agricultural productivity of cereal and potato in the period 1993–1997 was lower by 2.2% and by 7.7% than in 1971–1975. This is due to the impact not only of Bełchatów opencast mine, which has a negative influence on the yield in the southern part of the voivodship, but also of the opencast mines located in the Konin Basin, which negatively affect the north-western area.

Table 2. The yield of selected crops and the dynamics of the yield depending on the distance from Bełchatów opencast mines (according to the data from the analyzed voivodships).

Group	Average Yield in 1971–1975 Years [$t \times ha^{-1}$]		Average Yield in 1993–1997 Years [$t \times ha^{-1}$]		Dynamic [%]	
	Cereal	Potato	Cereal	Potato	Cereal	Potato
Group I	21.8	162.1	24.1	170.4	110.7	105.1
Group II	24.3	187.3	25.1	175.4	103.2	93.7
Group III	28.5	196.6	34.6	216.2	121.5	110.0

Sources: Based on [49–57].

The launching of the field drainage system in Szczerców in 2000 and the poor availability of data on the yield until 1997 make it impossible to fully estimate the impact of Bełchatów opencast mine on agriculture, especially after 2000, when the full influence of the opencast mine became obvious and the area of the depression cone reached its maximum range. To make a proper assessment of the possible range of influence of Bełchatów opencast mine after 1997, a comparative analysis was performed of the changes in the level of the yield in the area of the impact of Bełchatów opencast mine and the opencast mines located in the Konin Basin. For the Konin Basin, the base period was the average yield from 1956 to 1960, marked as year 1 in Figure 2, and for Bełchatów opencast mine it was the average yield from 1971 to 1975. The dynamics of the decline in the level of the yield in Areas I and II compared to the dynamics of the yield in Area III for individual opencast mines were different (Figure 2). In the case of the area of Bełchatów, over the period of 23 years, the yield of cereal in Area I fell by 9.9% compared to the yield in Area III, on average, while in the case of the Konin Basin, the decline in the first 23 years was 5.6%. For potatoes, the difference in agricultural productivity was 6.5% and 4.4%, respectively. The differences in the level of agricultural productivity resulted from the fact that in the case of the Bełchatów opencast mine the relative decrease in the yield occurred in the first few years, whereas in the case of the deposits in Konin the decrease in the yield occurred with a delay of several years. However, in the following 15 years, the average decline in the yield for the area of Konin was larger and amounted to 17.2% for cereal and 14.0% for potatoes, which translated into 10.2% and 8.2% decline in the yield respectively over the period of 38 years since the opencast mine in Konin was launched.

Figure 2. The dynamics of the yield of cereal and potatoes in Area I and II compared to the dynamics of the yield in Area III for Bełchatów opencast mine (base period—1971–1975 years) and the Konin Basin (base period—1956–1960 years) at the voivodship level: (a) cereal; (b) potato. Source: based on [50–58].

Therefore, it should be assumed that the decline in the yield in the area of influence of Bełchatów opencast mine was still the case after 1997. The above might be confirmed by a slower increase in the yield of cereal, by approximately 5.2%, in the period 1997–2013, in the area of present Łódzkie Voivodship (which also includes voivodships located outside the area of the influence of Bełchatów opencast mine) compared to the neighboring voivodships [58]. In the context of the trends, Figure 2, it was assumed that in the area of influence of Bełchatów opencast mine, Area I, the average decrease in the yield of cereal 24–38 years after the launch of the field drainage system, will be similar to the decrease in the yield in the area of Konin opencast mine. The average decrease in the yield of cereal for the whole period of 38 years of the drainage of the deposits in Bełchatów, adopted for calculation of external costs for Area I, was approximately 14.8%. In the case of potatoes, for 24–38 years after the launch of the drainage system there was a faster increase in the yield in the present Łódzkie Voivodship compared to the neighboring provinces; therefore, for the whole period of the impact, the level of decline in the yield was assumed to be the same as for the Konin Basin, i.e., 7.7%.

In the case of the Bełchatów deposit, the decline in the yield in Area II was larger than in Area I and it was also greater than in Area II, that is the Konin Basin. This was related, as mentioned earlier, to a decline in the level of the yield in Sieradzkie Voivodship and with a simultaneous systematic increase in the yield in the areas of the other analyzed voivodships. Due to the difficulty of determining the actual impact of Bełchatów opencast mine on the level of the yield in Area II, the level of the loss was assumed to be the same as the loss in the area of the Konin Basin. For the entire period of the impact of the opencast mine, the loss was 3.8% for cereals and 3.3% for potatoes.

The data in Figure 3 do not give a clear answer regarding the impact of Bełchatów opencast mine on cattle or pig population. The observed changeability of the population of farm animals in Area I compared to the changes in the livestock in Area III, during the period analyzed, could be assumed to be the result of ordinary changes in local agricultural conditions. In the case of Area II, a systematic decrease in the size of livestock was observed compared to Area III, which may indicate the loss in animal production.

Figure 3. The dynamics of the livestock of cattle, cows, pigs, sows and the number of Large Size Units in Area I and II compared to the dynamics of the livestock in Area III for Bełchatów opencast mine (on the voivodship level): (a) cattle (without cows) and cows; (b) pigs (without sows) and sows; (c) large size unit (LSU). Source: based on [49–57].

A slightly different picture of the impact of Bełchatów opencast mine on animal production is presented in Figure 4. There is a visible significant impact on livestock production in the districts located up to 40 km away from the opencast mine. In the case of the districts located up to 60 km away from the opencast mine, the systematic decline in livestock compared to the areas located 80–100 km away from the open cast mine was noticed only for cattle and cows. In the case of pigs and sows, those areas were characterized by the greatest increase in the number of those animals, which was related to a large increase in the size of livestock in the area of Piotrków, mainly due to the increased importance of contract fattening. The popularity of the above contributed to the reconstruction of herds for fattening in the districts of Bełchatów and Radomsko located 20–40 km away from Bełchatów opencast mine. A detailed analysis of the changes in the livestock in individual districts located within 100 km of the Bełchatów opencast mine shows great diversity. In the case of 3 districts located up to 40 km away from the opencast mine, the decrease in the population of cattle was not compensated by an increase in the number of pigs and sows. In the case of other districts, a large decline in the population of one type of animal species was usually compensated by an increase in the number of other types of animals, which indicated the growing specialization of districts and regions in livestock production.

Figure 4. The dynamics of changes in the number of cattle, cows, pigs, sows and large size units in the districts depending on the distance from Bełchatów opencast mine compared to the dynamics of changes in the size of livestock in the districts located 80–100 km away from the mine: (a) cattle (without cows); (b) cows; (c) pigs (without sows); (d) sows; (e) LSU. Source: based on [50,58].

Due to the lack of proper data concerning the impact of Bełchatów opencast mine on livestock production in specific voivodships, to estimate the external costs for the deposits in Żłoczew the data on the changes in animal production at the district level converted to LSU was used. For the analysis, only the areas located up to 60 km away from the opencast mine were taken into account. In the case of districts where there was an opencast mine located, the population of the animals under study decreased by 11.0% on average in the entire period under review—13.8% in the districts located 20–40 km away from the opencast mine and 6.7% in the districts located 40–60 km away from the opencast mine.

Based on the conducted analysis, it can be noticed that for the probability level $p \leq 0.05$, the initial null hypothesis of equality of the dynamics of the changes in the yield of cereal and potatoes can be rejected ($p = 0.0000$). Thus, the distance from the mine had a statistically significant effect on the yield in the three groups of voivodships under review (Table 3). The results of the multiple comparison test indicate that for cereal, the difference in the growth rate of the yield between Area I and Area II was not statistically significant. However, for both types of crops analyzed, the difference in the pace of the changes between the region located furthest from the opencast mine (Area III) and Area I and II was statistically significant and the significance level was 0.05. As was expected, the growth rate in the yield in the region located outside the area of impact of the opencast mine was significantly higher.

Table 3. The results of the Kruskal-Wallis multiple comparisons test performed to analyze the dynamics of the changes in the yield of selected crops (according to the data from specific voivodships).

Cereals		Potatoes	
test Kruskal-Wallis		test Kruskal-Wallis	
H (2, N = 66) = 28.3275; p = 0.0000		H (2, N = 111) = 46.25747; p = 0.0000	
post-hoc comparisons			
group I vs. II	0.19488	group I vs. II	0.00023
group I vs. III	0.00202	group I vs. III	0.01444
group II vs. III	0.00000	group II vs. III	0.00000

Based on the data received from the districts, there was no difference in the pace of changes in livestock production in the five areas, regardless of the distance from an opencast mine, for the period from 1975 to 2010, for cattle, cows, and livestock density in LSU (Table 4). The dynamics of changes was significantly different in the case of pigs and sows. Based on the analysis of the obtained data, from the point of view of the hypothesis of the impact of an opencast mine on the animal population, it can be noticed that in the case of districts located in the area near Bełchatów opencast mine, the rate of change in the population of pigs did not differ from the pace of the changes in districts located 20–40 km away from the opencast mine, however, it was significantly different in the districts located 40–60 km away and 80–100 km away from the opencast mine. The analysis of the input data indicates that the pace of changes in livestock was faster in the districts located 20–40 km away from the opencast mine than in the district of Bełchatów. Regarding the dynamics of the changes at the voivodship level, a significant difference in the rate of the changes in the livestock was recorded only for sows for the voivodships in Group II compared to the voivodships in Groups I and III (Table 5).

The results of the analysis of variance indicate that for the assumed significance level of $\alpha = 0.05$ the null hypothesis that the mean values of the number of animals in the compared groups of districts are equal should be rejected (Table 6). The increase in the significance of the differences in the period from 2006 to 2010, compared to the years 1975–1979, was mainly the case of the livestock converted to LSU and sows for the districts located close to the opencast mine compared to the districts located further away from the opencast mine. The decrease in the significance of the differences was primarily the case of the population of cattle.

Table 4. The results of the Kruskal-Wallis multiple comparisons test * performed to analyze the dynamics of the changes in livestock (according to the data from the districts).

Indicator	Cattle	Cows	Pigs	Sows	LSU
test Kruskal-Wallis					
H (4, N = 175)	6.79541	5.55901	82.19775	47.57426	5.64238
p	0.1471	0.2346	0.0000 *	0.0000 *	0.2275
post-hoc comparisons					
do 20 km vs. 20–40 km	1.0000	1.0000	1.0000	0.4393	1.0000
do 20 km vs. 40–60 km	1.0000	0.2501	0.0000 *	0.0001 *	1.0000
do 20 km vs. 60–80 km	1.0000	1.0000	0.0726 *	1.0000	1.0000
do 20 km vs. 80–100 km	1.0000	1.0000	0.0000 *	0.2707 *	1.0000
20–40 km vs. 40–60 km	1.0000	1.0000	0.0000 *	0.0000 *	1.0000
20–40 km vs. 60–80 km	1.0000	1.0000	0.0901 *	0.0037 *	0.9961
20–40 km vs. 80–100 km	0.4912	1.0000	0.0000 *	0.0002 *	0.2309
40–60 km vs. 60–80 km	1.0000	1.0000	0.0000 *	0.0314 *	1.0000
40–60 km vs. 80–100 km	0.3514	1.0000	0.3899	0.2211	1.0000
60–80 km vs. 80–100 km	1.0000	1.0000	0.1084	1.0000	1.0000

*— $p \leq 0.05$.**Table 5.** The results of the Kruskal-Wallis multiple comparisons test * performed to analyze the dynamics of the changes in livestock (according to the data from the voivodships).

Indicator	Cattle	Cows	Pigs	Sows	LSU
test Kruskal-Wallis					
H (2, N = 105)	0.8107	0.2670	0.8303	9.6380	0.1869
p	0.6667	0.8750	0.6603	0.0081 *	0.9108
post-hoc comparisons					
group I vs. II	1.0000	1.0000	1.0000	0.0135 *	1.0000
group I vs. III	1.0000	1.0000	1.0000	1.0000	1.0000
group II vs. III	1.0000	1.0000	1.0000	0.0369 *	1.0000

*— $p \leq 0.05$.**Table 6.** Results of the analysis of variance regarding the significance of the differences in livestock for specific districts at the beginning and the end of the analyzed period (average for five years).

Indicator	Cattle		Cows		Pigs		Sows		LSU	
	1975–1979	2006–2010	1975–1979	2006–2010	1975–1979	2006–2010	1975–1979	2006–2010	1975–1979	2006–2010
Analysis of variance										
F	8.0281	3.7215	9.816	2.9987	4.7954	2.8436	4.6972	3.4328	8.1074	3.8956
p	0.0000	0.0068	0.0000	0.0212	0.0013	0.0271	0.0015	0.0108	0.0000	0.0052
Least significant differences test										
{1} vs. {2}	0.0697	0.5428	0.1517	0.9491	0.0926	0.6464	0.2294	0.0683	0.5170	0.0697
{1} vs. {3}	0.6538	0.9148	0.8076	0.4921	0.2935	0.1484	0.1360	0.5483	0.5376	0.6538
{2} vs. {3}	0.0387 *	0.3032	0.0756	0.3213	0.2732	0.2206	0.8443	0.0592	0.8873	0.0387 *
{1} vs. {4}	0.0253 *	0.0601	0.0634	0.3095	0.0115 *	0.1132	0.0216 *	0.0195 *	0.0365 *	0.0253 *
{2} vs. {4}	0.7740	0.1141	0.7336	0.2164	0.3815	0.1595	0.2032	0.6843	0.0716	0.7740
{3} vs. {4}	0.0021 *	0.0007 *	0.0056 *	0.0037 *	0.0100 *	0.8078	0.1547	0.0027 *	0.0107 *	0.0021 *
{1} vs. {5}	0.8105	0.7618	0.3387	0.5899	0.5212	0.7772	0.4702	0.8654	0.7952	0.8105
{2} vs. {5}	0.0014 *	0.5732	0.0004 *	0.4031	0.0679	0.7261	0.3439	0.0019 *	0.4929	0.0014 *
{3} vs. {5}	0.1656	0.4169	0.0189 *	0.7184	0.3630	0.0162 *	0.0970	0.1188	0.4466	0.1656
{4} vs. {5}	0.0000 *	0.0012 *	0.0000 *	0.0020 *	0.0001 *	0.0073 *	0.0010 *	0.0000 *	0.0002 *	0.0000 *

Group symbol: {1}—up to 20 km; {2}—20–40 km; {3}—40–60 km; {4}—60–80 km; {5}—80–100 km. *— $p \leq 0.05$.

The levels of significance of the differences in the size of livestock in the three analyzed groups of voivodships are more noticeable. (Table 7). In both the initial and the final periods of the study, significant differences were recorded in the voivodships in Group II and III. In the case of provinces from groups I and III, at the beginning of the period, significant

differences in the level of stock were obtained only for pigs, sows, and LSU. In most of the others the level of significance decreased or did not change.

Table 7. Results of the analysis of variance regarding the significance of the differences in livestock for individual voivodships at the beginning and the end of the analyzed period (average for five years).

Indicator	Cattle		Cows		Pigs		Sows		LSU	
	1975–1979	2006–2010	1975–1979	2006–2010	1975–1979	2006–2010	1975–1979	2006–2010	1975–1979	2006–2010
Analysis of variance										
F	4.4239	4.3387	3.6278	3.8527	11.5614	4.6843	15.9750	4.4968	7.0029	7.0029
p	0.0181 *	0.0194 *	0.0352 *	0.0291 *	0.0001 *	0.0146 *	0.0000 *	0.0170 *	0.0024 *	0.0066 *
Least significant differences test										
group I vs. II	0.9396	0.9582	0.2855	0.2136	0.3599	0.0815	0.1773	0.3836	0.6150	0.2739
group I vs. III	0.0658	0.0659	0.4299	0.5106	0.0214 *	0.7820	0.0144 *	0.2326	0.0472 *	0.2198
group II vs. III	0.0124 *	0.0136 *	0.0105 *	0.0083 *	0.0000 *	0.0040 *	0.0000 *	0.0056 *	0.0012 *	0.0019 *

*— $p \leq 0.05$.

The large area of impact of the opencast mine and the increasing productivity of agriculture in the regions located within the area affected by Złoczew and Bełchatów opencast mines resulted in the high level of external costs incurred due to the launch of the Złoczew opencast mine (Table 8). The average value of external costs for the three variants adopted for the analysis was approximately €4.86 billion, which, with the estimated net electricity production of 398.2 TWh, gives €12.20 $\times$ MWh^{−1}. Since in 2019, the average price of electricity in Poland was €53.74 $\times$ MWh^{−1} and to calculate the external costs incurred by agriculture, the electricity prices should be increased by 22.7%. Among the adopted variants of changes in the productivity of crops and livestock, the value of the external costs will be the lowest if the technical and economic parameters in the entire period of the impact of Złoczew opencast mine are similar to current costs, and the value of incurred costs will be the highest if agriculture in the analyzed area develops at the pace at which German agriculture has developed over the past 38 years.

Table 8. External costs of exploitation of lignite from Złoczew deposit for 76 years of the impact of the opencast mine (million €).

Specification	Variant I	Variant II	Variant III	Average	€ $\times$ MWh ^{−1}
Plant production					
Open-pit mining area	61	71	97	76	0.19
Group I	2137	2529	3402	2689	6.75
Group II	1234	1445	1821	1500	3.77
Total	3432	4045	5320	4266	10.71
Animal production					
Open-pit mining area	3	3	4	3	0.01
up to 20 km	98	255	195	109	0.27
20–40 km	104	270	204	261	0.66
40–60 km	126	259	251	217	0.54
Total	331	787	654	591	1.48
All in total	3763	4833	5974	4857	12.20

6. Discussion

The estimated expected losses borne by agriculture is connected with uncertainty resulting from the multitude of influencing factors. Comparison of changes in yields and numbers of livestock in the regions affected by the impact of the opencast mines with the neighboring areas not affected by the impact of the opencast mines significantly reduces the uncertainty resulting from changes in macroeconomic, natural, and climatic conditions, which occurred similarly in the area affected by the opencast mines and regions outside of this area. However, the reaction of farmers in these areas to these changes may differ.

The risk of incorrect estimation of the impact of the opencast on agriculture also stems from the changes in the administrative division made in 1999, which does not allow for estimating the changes in the crop levels within and outside the Bełchatów opencast area. The slower growth rate in the present Łódzkie voivodship, where the Bełchatów opencast is located, as compared to the neighboring voivodships, suggests further deepening of the negative impact of the opencast after 1997, and the results obtained should be treated only as approximate. The risk of overestimation or underestimation of the obtained external costs for the Złoczew deposit also results from other uncertainties and factors described in Chapter 2. Despite these limitations and uncertainties, the cost estimates obtained should be treated as highly probable. Even a small correction of these results will not change the general conclusion that after taking into account the costs incurred in agriculture, the launching of the Złoczew open pit is not economically justified.

According to the analysis conducted, almost 88% of the external costs related to the extraction of lignite from the deposits in Złoczew are the result of the decrease in the yield of plant production. The above is the result of the specificity of production, in the case of which a decrease in the yield means not only a decline in the value of production but also a decrease of agricultural productivity by a similar value. Farmers, regardless of the level of the yield, have to perform all basic agro-technical tasks, use the standard quantity of means of production such as seeds, fertilizers, and plant protection products, and devote the same amount of time. The likelihood of this scenario is even greater due to ongoing climate changes. The area influenced by Złoczew opencast mine is located in central Poland and it is the region where steppe-formation processes are common phenomena due to very low rainfall. The region is also characterized by long periods of drought [69]. The observed systematic increase in global temperatures causes the increase in evaporation which reduces the amount of rainwater available to plants and the agricultural efficiency of precipitation [70,71]. The above-mentioned efficiency is also decreased by the latest changes in the nature of precipitation. The occurrence of convective precipitation and heavy rainfall instead of continuous precipitation has a particularly negative influence on agriculture [72–74]. According to research conducted in Germany, an increase in temperature by one-degree results in an increase in the amount of heavy rainfall by 6.5% [75]. Those processes also lead to a decline in the amount of subsurface water and a decrease in the level of the groundwater table. All of the above, in turn, lead to an increase in the dependence of crops on the level of groundwater [76,77].

Those trends are confirmed by the studies conducted in the Great Hungarian Plain, which showed a 0.21–0.60 m decline in the level of groundwater between 1986 and 2010 compared to the state from 1961 to 1985. Despite the insignificant correlation between the levels of groundwater and crop output, the potential impact of reduced level of groundwater on the production of corn was estimated to be $0.65 \text{ t} \times \text{ha}^{-1}$, i.e., 11.6 % of the average annual yield from 1986 to 2010. There was also stagnation in the level of the yield of wheat [76]. Regrettably, similar studies, despite the importance of the problem of lowering levels of groundwater in many regions of the world, are a rarely recorded element of the latest global environmental crisis, which can be a threat to food security. First of all, there is a lack of detailed data and no information collected over a long period, to analyze the progressive effects of lowering levels of groundwater on a regional scale [76]. Poland also faces the above-mentioned issues. Although, the problem of the decrease of the level of groundwater is obvious, there are no comprehensive and long-term analyses on how common and serious this phenomenon is. Thus, it is difficult to assess whether the observed decline in the yield in the area of the Great Hungarian Plain is typical for this region of the world.

The observed decrease in the level of cereal and potato yield over the period of 23 years since the launch of Bełchatów opencast mine in the area of Piotrkowskie Voivodship is similar to the decrease in the yield observed in the area affected by the opencast mine in the Konin Basin (Figure 2) and in the Great Hungarian Plain. A much larger drop in the yield, which was observed in the subsequent years of the operation of the mine in the

Konin Basin, suggests a high probability of the occurrence of similar trends also for the coal deposits in Bełchatów.

Further, in the case of the deposits in Żłoczew, a similar pattern of the changes in the yield should be expected, although, in this case, there is a possibility of a greater loss. It is related to an increase in the sensitivity of crops to water deficiency along with an increase in agricultural productivity [78,79] and with the expected further increase in the yield of plants in Poland, including the region affected by the opencast mine in Żłoczew. What is more, the increase in the amount of water used by arable crops, which is proportionate to the increase in the yield, means that further increase in the yield may be difficult in the case of the groundwater table lowering, even though in the neighboring areas the increase in the yield will continue [80]. The feasibility of this scenario is confirmed by a decrease in the yield of cereal and potato in the period from 1971 to 1997, in Sieradzkie Voivodship, which was affected by both Bełchatów opencast mine and the opencast mines in the Konin Basin.

Groundwater is of key importance during dry periods and for many cultivated plants water stored in the upper layers of the soil can account for 50%–100% of the total use of water [77,81–87]. The above is also important because of the increasing frequency of rain-free periods and rising average air temperature. The forecasts on climate change indicate a further increase in temperatures in Europe and a multiple increase in the frequency of centennial drought in Europe, including Poland. A centennial drought is a drought never recorded in a certain area in the 20th century [88–90]. If the forecasts prove correct, the estimated external costs caused by the construction of a new opencast mine will be even higher. According to research conducted in the Czech Republic for the years 1961–2000, during severe drought, the yield of grain decreased by 25%–35%, depending on the type of species (average yield during the period under review of approximately $3.5 \text{ t} \times \text{ha}^{-1}$), the yield of potato decreased by approximately 20% (average yield of $16.9 \text{ t} \times \text{ha}^{-1}$), and the yield of rapeseed by 25% (average yield of $2.2 \text{ t} \times \text{ha}^{-1}$). The above-mentioned studies confirmed the relatively high drought tolerance of corn, and the decline in the yield was not more than 10% (average yield of $4.2 \text{ t} \times \text{ha}^{-1}$) [91]. Since the level of the yield obtained in the period under study was low, it should be expected that for the forecasted higher level of the yield in the area of the influence of Żłoczew opencast mine, the decrease in the level of agricultural productivity may be even higher during the periods of severe drought.

The drop in the yield during periods of drought depends on the type of species of the cultivated plant and its sensitivity to the lowered level of the groundwater table. In the case of wheat, for instance, the optimum growth of the plant is guaranteed by the level of the groundwater table at 0.7–1.6 m and in the case of corn at 1.0–3.0 m [76,78,86,92–94]. The level of groundwater table being lower than 4.0 m leads to a significant reduction of water stored in the upper layers of soil and the need for plants to use only rainwater. An example here, is research conducted in the Inland Pampas, during two growing seasons (2006/2007 and 2007/2008), according to which the yield of wheat, soybean and corn in the areas with the optimum level of groundwater was 3.7, 3.0, and 1.8 times larger than the yield in the regions where the water table was located below 4.0 m [93].

Studies conducted for Bełchatów opencast mine indicate a dynamic decline in the level of groundwater already in the first years of dewatering the mine, which explains, to some extent, the significant decrease in the yield that was noticed since the launch of the opencast mine. In the years 1982–1985, i.e., 6–9 years after the launch of the drainage system of the opencast mine near Brudzice, which is a town located approximately 6 km away from the southern edge of the opencast mine, the level of groundwater was lowered by approximately 5.22 cm per month, with the initial level of groundwater at 356 cm, and in Woźniki—a town located approximately 10 km away from the edge of the mine—the level of groundwater dropped at the rate of 1.1 cm per month; the initial level was at 244 cm. The sub clay water-bearing level was dewatered at the same time. In Ligota Wielka, a town located approximately 9 km away from the edge of the mine, the decrease in the level of groundwater table was at the pace of 9.14 cm per month [95]. According to another study, in places located at the same distance from the opencast mine, the level of groundwater table,

even during the period of high precipitation, was lower than 200 cm, although there were places where the level of groundwater table was at 200 cm [96–99], which might have been caused by the irregularity of the area of the depression cone and the impermeable layers which hold water. The above-mentioned areas are used to conduct comparative analyses of moisture conditions of the soil. For the majority of the analyses, there is one conclusion: “There is no negative impact of Bełchatów opencast mine on the level of moisture of arable land, regardless of the distance of the place from the opencast mine” [96–101] or “the impact is insignificant” [102]. According to the review of the results of the research, in the case of soil layers located up to 200 cm below the surface, where there was groundwater, the level of soil moisture at a depth of 25 cm and 45 cm was approximately 25% and it was higher by approximately 10 percentage points than in the layers where there was no groundwater [97–99]. To investigate the above, there was an experiment performed, the results of which are very interesting. It was a laboratory assessment on the effect of the capillary action in soil on the moisture of the top layers. It was proved that groundwater is important for the productivity of soil and plants can access water via their root system thanks to the capillary action, additionally, within the range of a depression cone, where there is no groundwater, the possibilities of using rainwater by plants are also limited [103].

A similar level of humidity of soil may be the evidence that dewatering of a mine does not, or may not, pose a threat to water management and agricultural losses such as reduction of the yield of cultivated plants, and the decrease in the yield depends on many other factors, including the direction of the water flow and the amount of rainfall [99,104–111]. Moreover, lower levels of groundwater might be a consequence of deforestation, intensification of agriculture, river regulation land reclamation, climate change and higher temperatures, or the increase of the level of precipitation in winter at the expense of the amount of precipitation in summer [99,112,113]. The above are not dominant factors that affect the level of groundwater table in the areas surrounding opencast mines.

There are also limited options for large-scale irrigation as it involves drawing water from deeper layers of soil and high costs associated with the construction and operation of irrigation systems. Launching irrigation systems on a larger scale delays the process of restoration of water surface and, in extreme cases, prevents it, which permanently limits the possibility of intensification of agricultural production. The above was confirmed by various research conducted in different regions of the world where overexploitation of underground resources led to a decline in the level of groundwater. The examples here are the Midwestern regions of the United States [114], the intensively irrigated North China Plain [115], and Syria [116], where there was a decrease in the level of groundwater by several dozen meters and a collapse of agricultural production in vast areas. Moreover, agriculture in those regions depends on costly irrigation and if it is not possible to organize it the yield varies according to the amount of rainwater.

The research conducted on external costs show that opencast lignite mining has a negative impact on the yield in large areas located around the mine, which is confirmed by analyses of the deposits in Bełchatów and in the Konin Basin. Nevertheless, it is necessary to conduct more research for other opencast mines.

According to the analysis conducted, there are relatively low costs incurred by livestock producers. This is mainly due to the decline in the number of cows and pigs over the last 10 years and the stabilization of cattle population in the areas affected by the opencast mines, as well as a much smaller area (almost 50% smaller), where livestock production is affected by Bełchatów opencast mine. It might be assumed that in the case of a forecasted slight decrease in the yield, the tendency of farmers to reduce or eliminate livestock production is the same as in the areas located further away from the opencast mines. The loss of profits from plant production is so small that it does not affect the investment decisions regarding livestock production. The tendency of some farmers to increase the number of animals may be a response to the decline in profits from plant production, which is compensated for by the development of livestock production.

Interesting results are provided by a survey conducted in Poland among 190 farmers in a region of high intensity of agriculture, where an opencast lignite mine was planned to be launched. The farmers did not plan to reduce their livestock even if the level of the yield was going to fall to 10%. Every fifth farmer declared a reduction of livestock production by at least 20% if the yield of fodder fell by 10–20%, and another one third of the farmers would reduce the production if the yield fell by 20–30%. Complete abandonment of livestock production with a yield drop to 30% was confirmed by every fourth farmer, and another 44% of farmers would stop the production if the yields fell by 30–50% [29]. The survey indicates a relatively high sensitivity of animal production to a decrease in the yield by at least 10%, which is usually caused by the appearance of a depression cone. The above may be partly related to the dominance of small and very small farms, with a standard production of less than €25,000, in the case of which it is important to produce own fodder.

The location of the Żłoczew opencast mine is unfavorable from the point of view of the distance to large urban centers. It is located 72 km away from the center of Łódź, i.e., the area that, according to Sinclair's theory, should be designated for intensive agricultural production, including animal production [117]. According to the studies conducted for Poland, the areas located 50–100 km away from major urban centers are characterized by the highest cow and pig density [68,117,118]. The launch of an opencast mine in such areas disrupts the system, forcing an increased concentration of production in the neighboring regions.

The analysis conducted gives only the approximate external costs related to the planned launching of the opencast mine in Żłoczew. The demonstrated loss of 22.7% of the estimated net value of electricity production and the expected further increase in the costs related to the emission of CO₂ indicate that the plans to launch an opencast mine in Żłoczew should be abandoned. In order to fully estimate the costs, it is still necessary to estimate other external costs, primarily those related to coal combustion. Studies by various authors show that depending on the range of factors analyzed, study methodology, data availability, power plant efficiency, combustion technology, land population, and others, the spread of external costs varies considerably (Table 9). For example, in the case of Thailand, where only the impacts of PM₁₀ and NO_x emissions in sparsely populated areas were analyzed, while the Macy et al. study included sulfur dioxide, nitrogen oxides, dust particles, carbon monoxide and dioxide, volatile organic compounds, polycyclic aromatic hydrocarbons, and heavy metals, resulting in a difference in external costs of about 10 times. In the case of Bosnia and Herzegovina, brown coals with different calorific and sulfur contents were analyzed [32]. There was less disproportion in the case of the study of external costs associated with opencast coal mining and these were lower than in the case of the projected external costs for the Żłoczew opencast.

Table 9. External costs of air pollution caused by lignite combustion and opencast coal mining € × MWh^{−1}.

Study	Georgakellos [119]	Sakulniyomporn [120]	Büke, Köne [121]	Dimitrijević [122]	Coester [16]	Máca [26]	Wang [25]	Taranto [123]	Papagiannis [28]	Pepliński, Czubak [32]
Country	Greece	Thailand	Turkey	Bosnia and Herzegovina	Germany	Czech, Hungary, Poland	China	Turkey	Greece	Poland
Year of analysis	2003–2004	2006–2008	2007	2008	1995–2003	2010	2015	2018	2014	2021
Health impacts	No	Yes	Yes	No	Yes	Yes	Yes	No	Yes	No
External costs	43.9	6.8	1.8–35.2	2.7–19.2	11.1	58.1–77.5	63.8	36.3	5.0	8.7

Source: Based on [32].

This analysis is the first comprehensive estimate of external costs in crop and livestock production associated with the depression funnel created by opencast coal mining. It is necessary to carry out further studies of external costs for currently operating and planned opencast coal and other natural resources in other countries and on other continents, which will extend the knowledge of factors affecting crop production losses and the magnitude of

external costs in different regions of the world and with different agricultural structures. It will also reduce uncertainty about the value of estimated external costs.

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