

Article

Resource Assessment and Numerical Modeling of CBM Extraction in the Upper Silesian Coal Basin, Poland

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Abstract: The paper presents the assessment of the resources of methane considered as the main mineral in the most prospective selected areas of the Upper Silesian Coal Basin, Poland in the region of undeveloped deposits. The methane resources were estimated by means of a volumetric method at three depth levels, 1000, 1250, and 1500 m. A part of the Studzienice deposit comprising three coal seams, 333, 336, and 337, located in a methane zone was chosen for the numerical modeling of simulated methane production. The presented static 3D model has been developed using Petrel Schlumberger software. The total resources of methane in the area amount to approximately 446.5 million of Nm³. Numerical simulations of methane production from the selected coal seams with hydraulic fracturing were conducted by means of Schlumberger ECLIPSE reservoir simulator. Based on the simulations, it was concluded that, in the first six months of the simulations, water is produced from the seams, which is connected with the decrease in the rock mass pressure. The process prompts methane desorption from the coal matrix, which in turn results in a total methane production of 76.2 million of Nm³ within the five-year period of the simulations, which constitutes about 17% of total methane resources (GIP). The paper also presents a detailed analysis of Polish legislation concerning the activities aimed at prospecting, exploring, and extracting the deposits of hydrocarbons.

Keywords: coal seams; methane resources; numerical simulations; legal issues

1. Introduction

Coal bed methane (CBM) is a natural gas created as a result of the transformations of organic matter into bituminous coal, which, due to the sorption phenomena, was accumulated in different ranks of coal [1]. The sorption capacity of coal depends on various parameters, i.e., thermodynamic conditions within the coal seams, moisture, and petrographic content of coals, as well as the composition of the adsorbed gas [2–6]. The global geological resources of coal bed methane are estimated to range from 100 to 216 billion m³ with the recoverable CBM resources estimated at 24–42 billion m³ [7,8]. In the United States, both the recognition of exploitable resources and the production of CBM are well-developed. The recoverable resources of coal bed methane in the United States account for 9%–29% of the geological resources, whereas the exploitable ones constitute only 14% of the recoverable resources [9]. The CBM resources are subject to the same procedures concerning the prospecting, exploring, documenting, and production as the resources of conventional hydrocarbons. The feature that makes coal bed methane resources different from the conventional ones is connected with large variability of the parameters used to estimate the resources, which in consequence translates into a high level of uncertainty concerning the reported statistics. The application of deterministic methods

to assess the resources is encumbered with errors; therefore, it is recommended to use probabilistic forecasting, which takes into consideration the statistical variability of parameters—for example, Monte Carlo methods [10]. Companies which carry on exploration and production activities, as well as those which produce reports on CBM resources, most often apply the petroleum resource management system (PRMS) introduced in 2007 under the auspices of international oil industry companies [11]. The PRMS classification of hydrocarbons resources allows for the assessment of the range of uncertainty concerning the predicted volume of hydrocarbons, as well as the risk assessment of commerciality. In Poland, the classification of CBM as the main mineral is based on the criteria of recoverability stipulated by the Regulation of the Minister of Environment on the geological and investment report of a hydrocarbon deposit [12].

Pre-mine drainage of methane from coal seams is an important issue concerning the safety of coal miners in operating coal mines. In recent years, there have been some works associated with the pre-mining methane extraction from coal seams using surface directional wells [13–15].

New prospects regarding the utilization of coal bed methane in Poland started to appear in the 1990s when AMOCO, TEXACO, Metanel, and Pol-Tex Methane initiated in the period of 1991–1998 intensified works on CBM extraction in the Upper Silesian Coal Basin within the framework of their concessions [16]. The extraction method consisted in simultaneous opening out of multiple gas-bearing coal seams by means of vertical wells with perforation and the use of hydraulic fracturing technology. The method proved to be unprofitable in the case of the Upper Silesian Coal Basin due to the small capacity of methane production during the tests, which did not guarantee the project cost effectiveness. The most important geological factor responsible for the poor performance was the low permeability of the coal seams in the Upper Silesian Coal Basin [16].

Previous research was carried out by means of vertical wells, whereas currently there is a trend of applying the technology of directional (horizontal) drilling for the opening out of gas-bearing coal seams. Particularly good results were obtained for directional drilling combined with under-balanced drilling [17]. The horizontal drilling ensures large drainage area, whereas under-balanced drilling allows preventing the damage of the near-well zone [18]. Thanks to the application of the above drilling methods in the United States, Australia, and Canada, it has been possible to produce gas from poorly permeable coal seams whose exploitation, similarly to the CBM production in the Upper Silesian Coal basin, was previously considered uneconomical [19]. The first evaluations of CBM resources in the Upper Silesian Coal Basin were made in the early 1990s [20]. The underlying reason to provide such evaluation was the process of granting concessions for the CBM resources in Poland. The in-situ resources of methane were estimated by means of the volumetric method, which is commonly applied in the United States [21].

In consecutive years, various institutions (Table 1) recalculated the estimates of CBM resources. All the estimates encompassed in situ resources and were performed using the volumetric method; in the subsequent estimates, only the boundary conditions were changed.

Table 1. Coal bed methane (CBM) resources in the Upper Silesian Coal Basin.

Institution	CBM Resources (Million Nm ³)
Polish Geological Institute [20]	365
Katowice Geological Company [22]	no less than 300–320
Central Mining Institute [23]	442

Methane resources were estimated for the basic zone of methane-bearing coal seams according to the current criteria of recoverability, i.e., up to the depth of 1500 m for coal seams of a minimal thickness of 0.6 m and an average methane content higher than 2.5 m³/Mg_{daf}. Yet another verification of the resources of coal bed methane, considered as the main mineral, took place in 2006. In this report, the resources of CBM were estimated at 124.5 billion m³, including the areas of operating coal mines below the depth of 1000 m, the closed seams, and undeveloped areas (Table 2).

Table 2. Estimated recoverable CBM resources within the boundaries of the selected area.

Type of Seam	CBM Resources (Million Nm ³)
Seams in operating coal mines	42,050.2
Seams in closed coal mines	7184.2
Undeveloped seams	61,958.0
Separated areas	13,347.7
Total	124,540.2

In Table 2, methane resources were estimated according to the volumetric method (GIP)-based on the verification of methane resources in active coal mines (coal mine methane—CMM), undeveloped coal deposits (coal bed methane—CBM), and abandoned coal mines (AMM). Due to the fact that, in Poland, the geological criteria for the estimation of CMM are different from those for CBM, the methane resources in Table 2 take into account different boundary conditions for resource estimation: (a) for CBM—the depth of 1500 m, seams with thickness >0.6 m, methane capacity >4.5 m³/Mg_{daf}; and (b) for CMM—the depth of documented coal seams in the mine area, thickness >0.2 m, and methane capacity of 2.5 m³/Mg_{daf}.

Three-dimensional geological modeling of hydrocarbon resources plays a prominent role in the processes of prospecting, exploring, developing, and exploiting hydrocarbon accumulations. In this respect, Schlumberger Petrel software constitutes a tool for developing geological-structural models that enable the integration of geological and geophysical data, as well as the information concerning reservoir engineering. The package of petrel reservoir engineering core modules, combined with an ECLIPSE industry-reference simulator, provides a set of numerical solutions for forecasting the dynamic reservoir processes and for designing plans for the exploration, development, and production. The modeling of bituminous coal seams using Schlumberger Petrel software enables to perform numerical simulations of coal bed methane extraction by means of directional drilling from the surface [19,20], as well as computer simulations of enhanced methane recovery combined with injecting CO₂ into the coal seams-enhanced coal bed methane (ECBM) [24–31].

The aim of this article is the evaluation of the resources of coal bed methane considered as the main mineral for 19 undeveloped seams within the area of the Upper Silesian Coal Basin, as well as the selection of the most prospective areas in terms of methane resources and the estimation of in-place methane resources (GIP) at several depth intervals. Additionally, the study encompasses the development of numerical simulations of methane extraction from selected coal deposits in order to estimate the recoverable methane resources and calculate the possible value of recovery factor.

The methane resources were estimated by means of the volumetric method (GIP—Gas In Place). Three areas of the Upper Silesian Coal Basin were selected as the most prospective. The analysis allowed assessing the distribution of CBM resources in the vertical profile in the adopted intervals (a) from the roof of the zone to 1000 m, (b) 1000–1250 m, and (c) 1250–1500 m for the three prospective areas. The total recoverable reserves of CBM considered as the main mineral in the first region equal 17,243.3 million Nm³, in the second region—12,447.4 million Nm³, and in the third region—3887 million Nm³.

The Studzienice deposit was selected for the numerical modeling of CBM extraction. A structural parameter model of the coal-bearing Upper Carboniferous formations was developed, and the reservoir parameters were analyzed. The static model was supplemented with detailed reservoir parameters, as well as the thermodynamic properties of reservoir gases and fluids.

Within the framework of the study, numerical simulations have been performed for the process of methane extraction from selected coal seams by means of a multilateral well combined with hydraulic fracturing to enhance the production. In addition, numerical simulations of methane extraction using directional wells drilled from the surface were carried out, and a numerical model of the selected coal deposits was developed.

2. Materials and Methods

2.1. The Estimation of Coal Bed Methane Resources

The resources of coal bed methane considered as the main mineral were estimated for 19 undeveloped seams within the area of the Upper Silesian Coal Basin. The resources were estimated for the designated boundaries of the seams areas, similar to the resources of methane as an accessory mineral within the seams of operating coal mines. The total recoverable resources of methane as the main mineral amount to 60,125 million Nm³ [32]. For the purpose of the estimates of CBM resources, the following boundary conditions were adopted:

- the thickness of the seams >0.3 m,
- the depth—1600 m, and
- the methane content >4.5 m³/Mg_{daf}—only in the basic zone of methane-bearing coal seams.

The methane resources were estimated by means of the volumetric method (GIP—Gas In Place) at three depth levels—1000, 1250, and 1500 m (see Figure 1).

The volumetric method is one of the simplest methods of estimating resources; it requires the relatively smallest recognition of the deposit, especially in terms of identifying reservoir parameters; however, it is generally used only to calculate geological resources and, after adopting geological criteria, also the anticipated economic and subeconomic ones. The calculation of CBM gas resources (GIP—Gas In Place) using the volumetric method is based on the following formula:

$$GIP = A \cdot H \cdot M_{avg} \cdot \gamma \quad (1)$$

where

GIP = methane resources (m³),

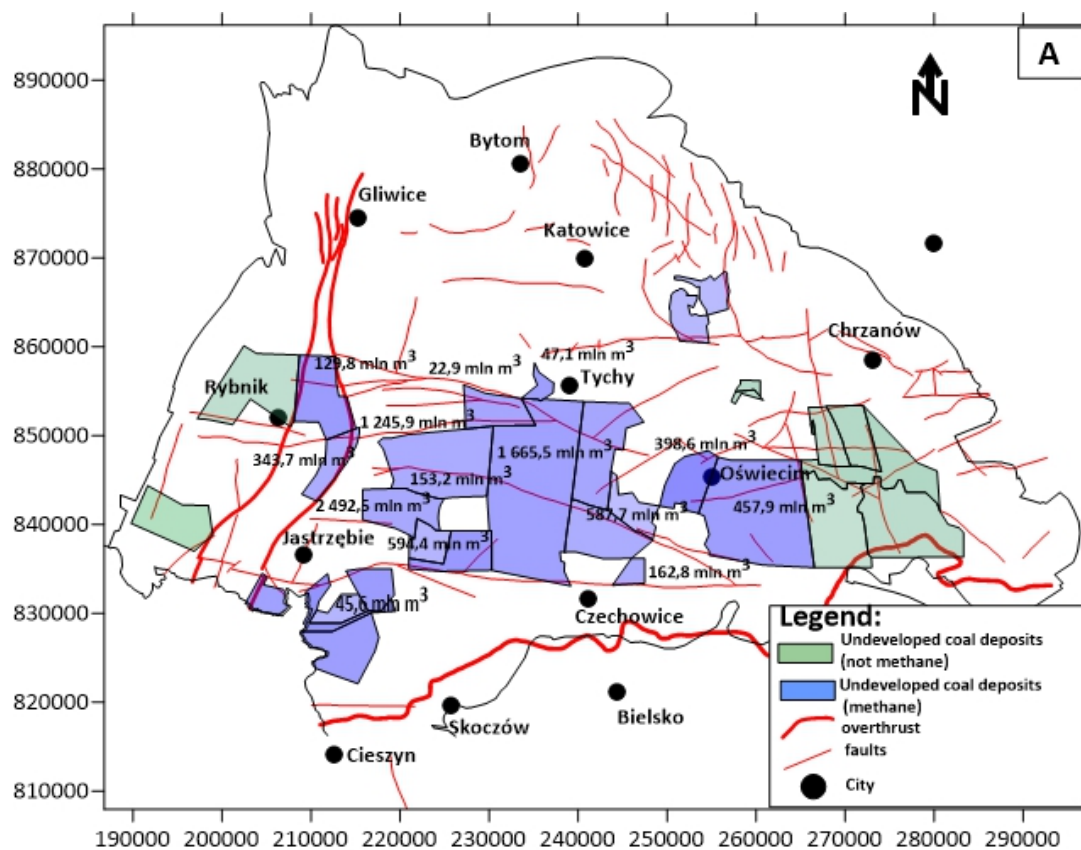
A = calculation area of methane resources (m²),

H = thickness of dry ash free coal (m),

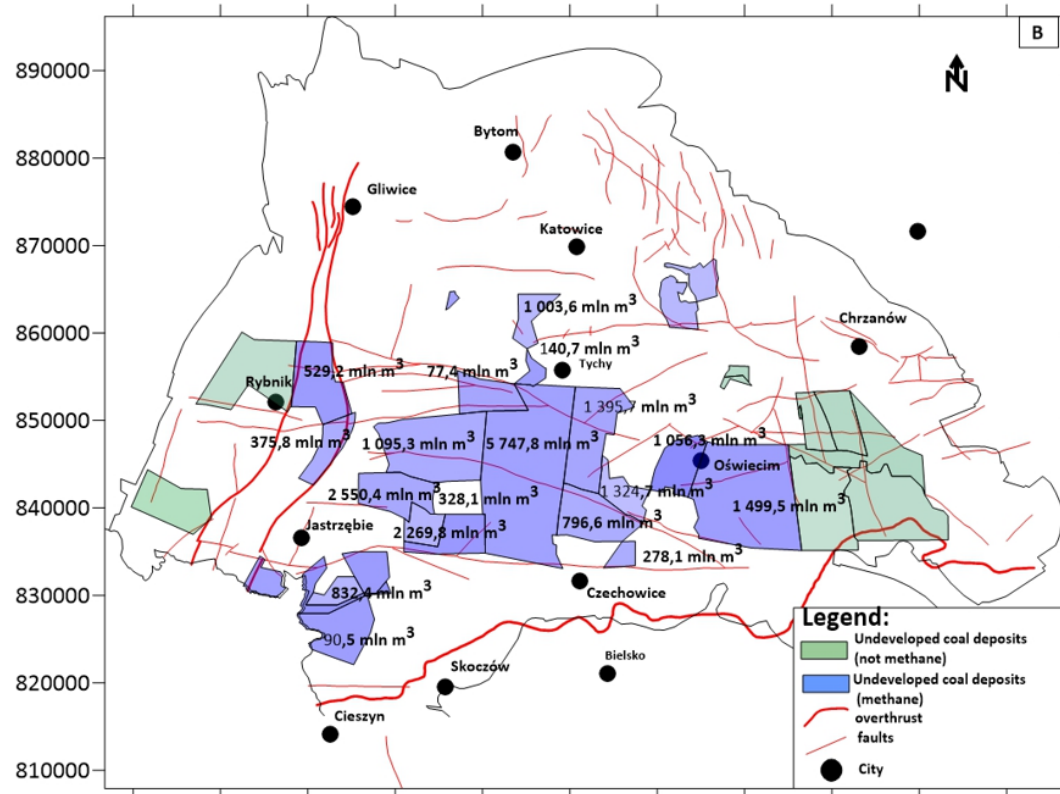
M_{avg} = average content of hydrocarbons (m³/Mg_{daf}), and

γ = density (Mg/m³).

For the purposes of further research, three areas of the Upper Silesian Coal Basin were selected as the most prospective in terms of methane resources. The analysis will allow assessing the distribution of CBM resources in the vertical profile in the adopted intervals for estimating resources (a) from the roof of the zone to 1000 m, (b) 1000–1250 m, and (c) 1250–1500 m for the three prospective areas. Next, a numerical model of the selected coal deposit was developed, and numerical simulations of the methane extraction using directional wells drilled from the surface to assess the potential developed resources were carried out.



(a)



(b)

Figure 1. Cont.

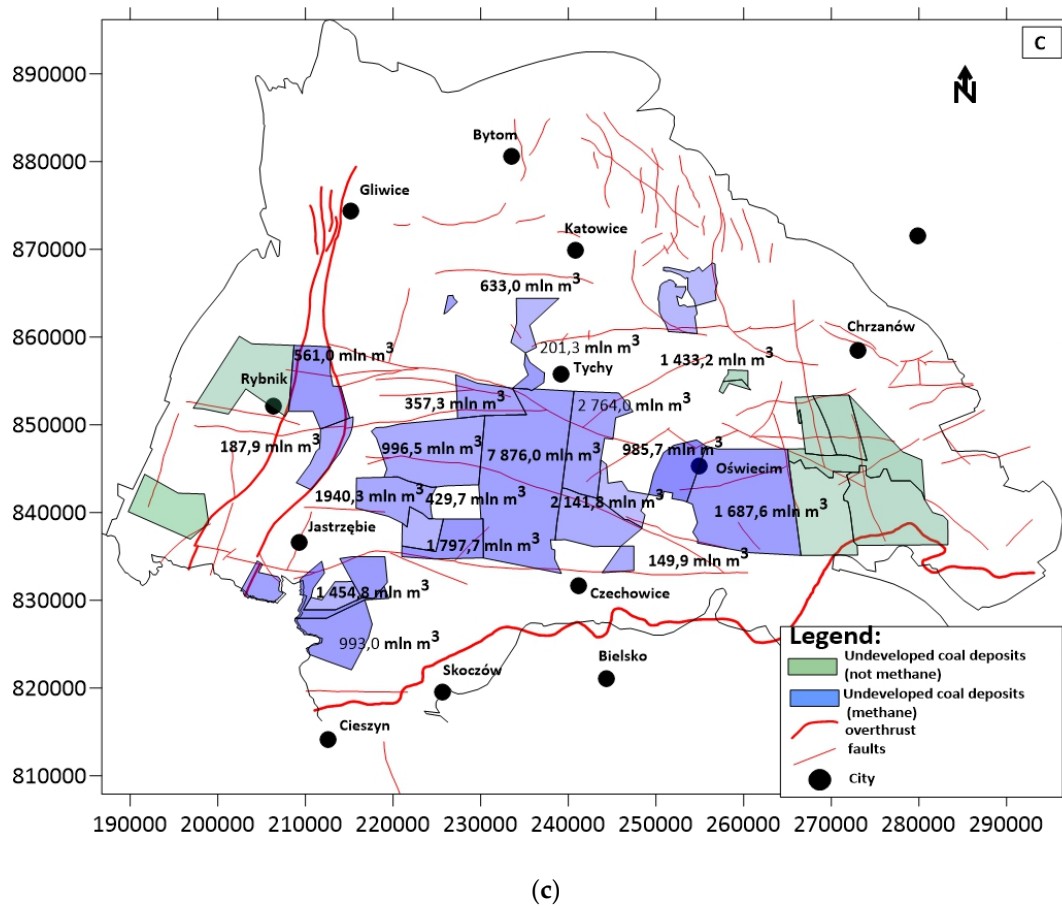


Figure 1. Maps of coal bed methane (CBM) resources occurring in undeveloped areas of the Upper Silesian Coal Basin, Poland for three depths: (a) up to 1000 m, (b) 1000–1250 m, and (c) 1250–1500 m.

2.2. Numerical Modeling of CBM Extraction

The ECLIPSE Simulator allows for the double porosity in the model. The model consists of two interconnected systems representing the coal matrix and the cleat system. Methane is stored by means of sorption in a poorly permeable coal matrix characterized by varied porosity in comparison to the cleat system where the phenomenon of desorbed gas flow takes place. Accordingly, in double-porosity models, the number of layers is doubled, whereas the calculations during the simulation are conducted for a double number of cells.

The model of gas adsorption on coal for the different components is described in ECLIPSE 300 by means of the extended Langmuir isotherm [33]. The adsorption capacity is a function of the pressure and free-gas phase composition. For each of the gases, it is required to introduce Langmuir isotherm parameters, i.e., the Langmuir volume constant V_i and the Langmuir pressure constant P_i . These parameters are typically determined based on experiments. Different isotherms can be used in different regions of the field. The multicomponent adsorption capacity is calculated by means of the following equation:

$$L(p, y_1, y_2, \dots)_i = \theta \frac{P_s}{RT_s} \left(V_i \frac{y_i \frac{p}{P_i}}{1 + \sum_{j=1}^{nc} y_j \frac{p}{P_j}} \right) \quad (2)$$

where

θ = scaling factor,

P_s = pressure at standard conditions,

R = universal gas constant,

T_s = temperature at standard conditions,

V_i = Langmuir volume constant for component i ,
 P_i = Langmuir pressure constant for component i ,
 y_i = hydrocarbon mole fraction in the gas phase for component i , and
 p = pressure.

For the special case of a single component, the extended Langmuir isotherm is identical to the usual Langmuir isotherm giving the storage capacity as a function of pressure only:

$$L(p) = \theta \frac{P_s}{RT_s} \left(V \frac{\frac{p}{P}}{1 + \frac{p}{P}} \right) \quad (3)$$

where V is the maximum storage capacity for the gas, referred to as the Langmuir volume constant, and P is the Langmuir pressure constant. The constants used in the extended Langmuir formulation can hence be estimated from a series of single-component gas experiments.

Time-dependent diffusion in ECLIPSE 300, i.e., the diffusive flow between the matrix and the fracture, is given by:

$$F_i = DIFFMF \cdot D_{c,i} \cdot S_g \cdot RF_i \cdot (m_i - \rho_c L_i) \quad (4)$$

where

m_i = molar density in the coal matrix, and
 $DIFFMF$ = matrix fracture (or multi-porosity) diffusivity.

It is possible to scale the adsorption capacity, keyword LANGMULT, by a factor for each cell in the grid. Typically, this can be used to account for differences in ash or moisture contents.

ρ_c = rock density (coal density),
 $D_{c,i}$ = diffusion coefficient (coal) component i ,
 RF_i = readsorption factor component i ,
 S_g = gas saturation for a desorption value of unity is used, and
 $\rho_c L_i$ = equilibrium molar density of adsorbed gas.

The matrix-fracture diffusivity is given by:

$$DIFFMF = DIFFMMF \cdot VOL \cdot \sigma \quad (5)$$

where

$DIFFMMF$ is the multiplying factor input,
 VOL is the coal volume, and
 σ is the factor to account for the matrix-fracture interface area per unit volume.

Often the component's sorption time is a quantity that is easier to obtain than the diffusion coefficients. For desorption, we write the flow as:

$$F_i = (VOL/\tau_i) (m_i - \rho_c L_i) \quad (6)$$

where

$\tau_i = 1/(D_{c,i} \cdot DIFFMMF \cdot \sigma)$ is called the sorption time.

The parameter controls the time lag before the released gas enters the coal fracture system.

The sorption times are given by the diffusion coefficients, $DIFFCBM$, and the matrix-fracture interface area, $SIGMA$, together with the multiplying factor $DIFFMMF$. If the sorption times are known, a value of unity can be assigned to σ and $DIFFMMF$. The diffusion coefficients can then be assigned to the reciprocal of the sorption times [33].

Simulator ECLIPSE 300 requires predetermining the initial gas concentration in the coal by means of inputting the gas volume to the mass of the base rock (sm^3/kg). The ECLIPSE software defines the sm^3/kg unit as a cubic meter of gas (pressure of 1 atm = 1013.25 hPa and temperature of 15.56 °C) per one kilogram of coal under in-situ conditions.

The presented static 3D model has been developed using Petrel Schlumberger 2010.1 software [34]. The above model constituted the foundation for creating a dynamic model encompassing the simulations of the process of CBM extraction by means of directional drilling technology combined with hydraulic fracturing of the rock mass to enhance methane production. The numerical simulations were performed by means of the 2011.3 compositional version of the ECLIPSE simulator with the option of coal bed methane [33]. The numerical model was constructed for the selected area of research encompassing the region of an undeveloped Studzienice deposit. During the first phase of the study, a static model of the whole Studzienice play, displaying the following documented seams: 211, 213/1, 214/1, 214/1-2, 215/2, 301, 303, 308, 310, 312, 315, 318, 320/1, 321, 324, 328, 333, 336, and 337 and taking into consideration the occurrence of potential faults, was constructed. Within the model, the coal-bearing formations of productive carboniferous demonstrate considerable a tectonic engagement of the rock mass (Figure 2).

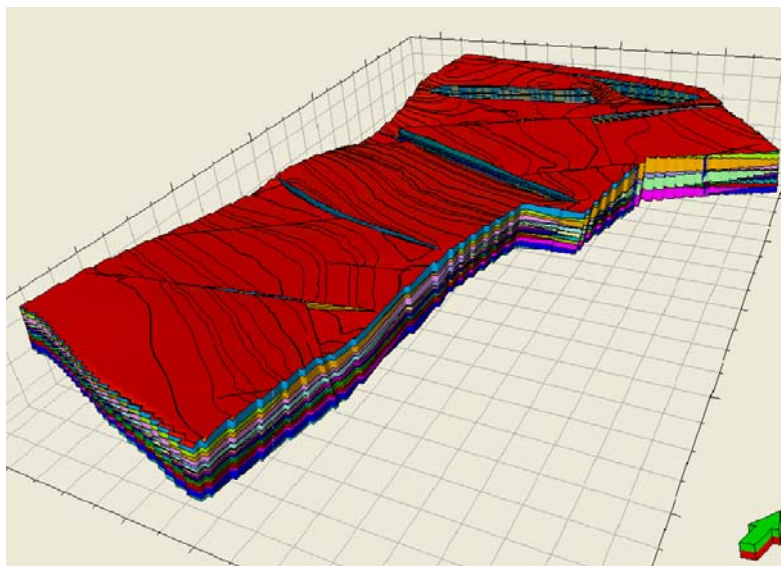


Figure 2. Structural model of bituminous coal seams.

The area of the modeled region equals 55.5 km². The static model was used for developing dynamic simulation models for the selected seams 333, 336, and 337 of the high-methane content zone. Within one tectonic block, the exploration and production wells were located. The first designed well, Studzienice V, was a vertical one and performed the function of an exploration well by means of which the analyzed coal seams were drilled. The next well consisted of three branched directional boreholes (Studzienice 1H, Studzienice 2H, and Studzienice 3H) drilled from a vertical section of the well, which enabled the simulation of methane exploitation processes. The depths of the deposition of the seams within the selected model block were in the ranges of 925–1023 m, 1007–1102 m, and 1021–1116 m for seams 333, 336, and 337, respectively. Figure 3 presents the deposition of seam 337 within the selected tectonic block.

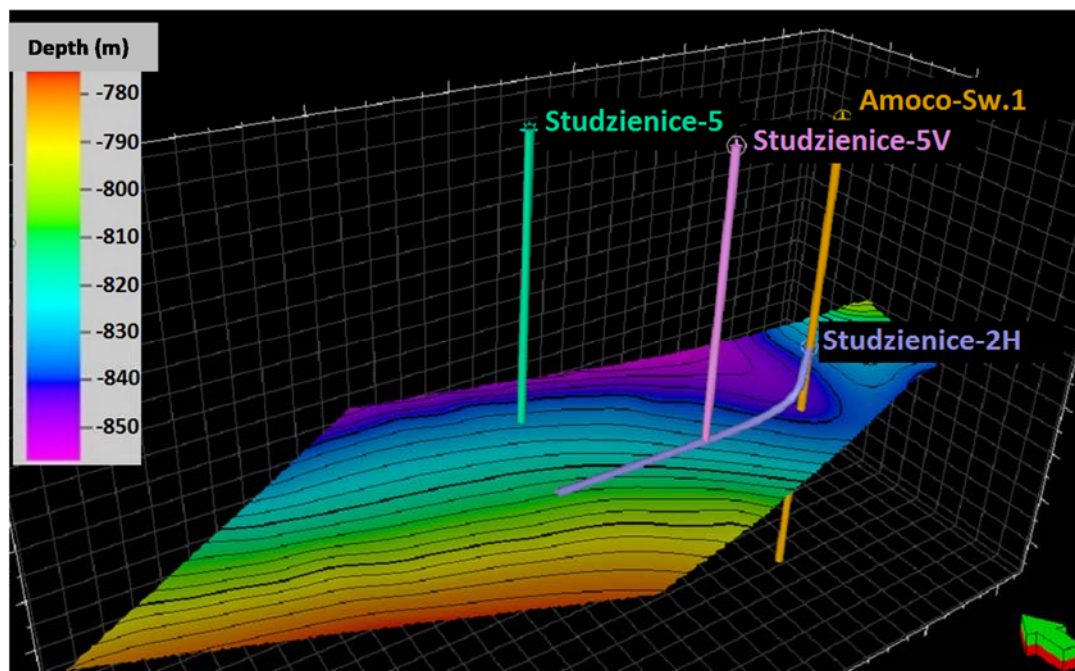


Figure 3. The deposition of seam 337 within the selected tectonic block.

The area of the modeled region equals 2.62 km². The thickness of the modeled region ranges from 70.5 to 113 m. A horizontal resolution of a 10 × 10-m interpolation grid was applied. Figure 4 demonstrates the developed model, which comprises 5 layers and 219,375 cells. The parameters of the numerical model are listed in Table 3.

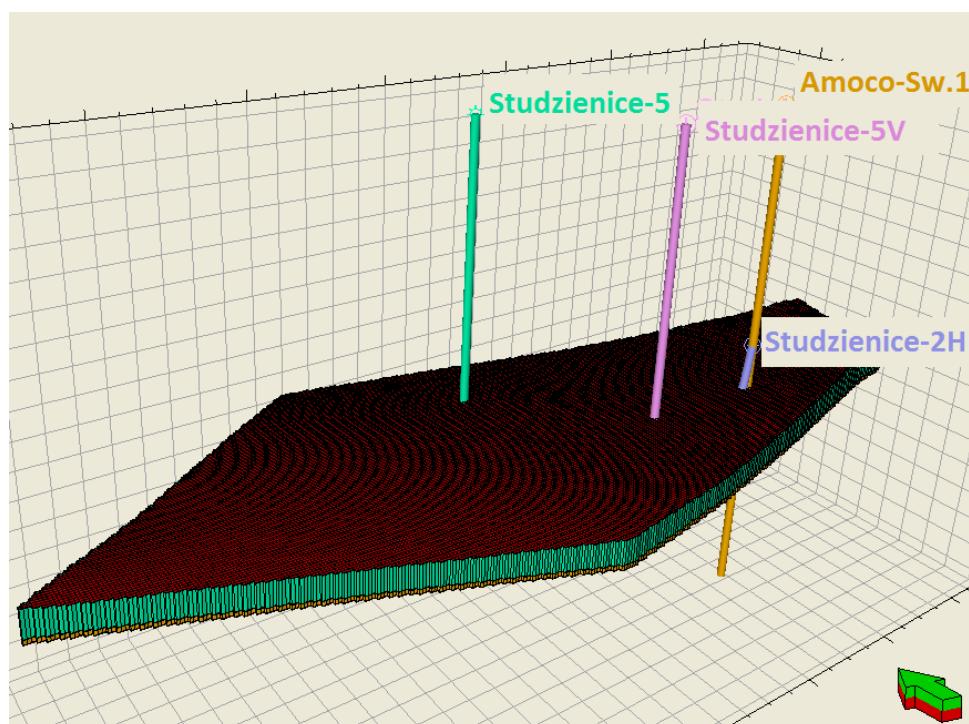


Figure 4. Simulation model of CBM extraction from seams 333, 336, and 337.

Table 3. Structural parameters of the simulation model for CBM extraction.

Calculation Interval (Depth, M)	Recoverable Reserves of CBM Considered as the Main Mineral (Million Nm ³)
Average coal seam thickness (m)	1.5
The area of the model (km ²)	2.62
Horizontal resolution of the interpolation grid (m)	10 × 10
Vertical resolution of the model (m)	1.5
Fracture porosity (%)	0.5
Permeability X, Y, and Z (mD)	1.5

In the developed numerical model, a series of numerical simulations have been performed for the process of methane extraction from selected coal seams by means of a multilateral well combined with hydraulic fracturing to enhance production. For the purpose of simulating the process of CBM extraction, a compositional version of ECLIPSE simulator with the option of coal bed methane was used. This version of the simulator takes into consideration the major mechanisms responsible for the flow of water and gas within the coal seam, namely, the desorption of gas from the coal matrix into the cleat system, diffusion in the coal matrix according to Fick law, and Darcy's flow in the fractures [33]. The ECLIPSE 300 Simulator used in the study allows for the double porosity in the model. Therefore, the model consists of two interconnected systems representing the coal matrix and the cleat system. Methane is stored by means of sorption in a poorly permeable coal matrix characterized by varied porosity in comparison to the cleat system where the phenomenon of desorbed gas flow takes place. Additionally, gas adsorption isotherms described in ECLIPSE 300 by means of an extended Langmuir isotherm are applied in the model [30]. Besides the parameters of the extended Langmuir isotherm, the developed model also incorporates the coal density, methane diffusion coefficient, and minimum production pressure. The ECLIPSE software defines the sm³/kg unit as a cubic meter of gas (at the pressure of 1 atm = 1013.25 hPa and temperature of 15.56 °C) per one kilogram of coal under in-situ conditions [33].

In the developed model, laboratory data obtained during the execution of the Reduction of CO₂ emission by means of CO₂ storage in coal seams in the Silesian Coal Basin of Poland (RECOPOL) project and a pilot CBM project executed by TEXACO were used [16,34–37]. Detailed parameters for developing the model are compiled in Table 4.

Table 4. Parameters used for modeling the CBM extraction.

Parameter	Seams 333, 336, and 337
Coal density, kg/m ³	1330.00
CH ₄ Diffusion coefficient, m ² /d	0.0000685
Initial pressure, bar	115–120
Min. Production pressure, bar	5.00
333 coal seam depth, m	925–1023
336 coal seam depth, m	1007–1102
337 coal seam depth, m	1021–1116
Extended Langmuir Isotherm Parameters	
CH ₄ volume V _L , sm ³ /kg	0.0205
CH ₄ pressure P _L , bar	42.00
CO ₂ volume V _L , sm ³ /kg	0.0320
CO ₂ pressure P _L , bar	19.03

3. Legal Aspects of the Activities Concerning the Prospection, Exploration, and Extraction of CBM in Light of the Act on Geological and Mining Law

Under the provisions of the Act of 9 June 2011, Geological and Mining Law (i.e., of 4 April 2019, the Journal of Laws of 2019, item 868; hereafter: Geological and Mining Law), the deposits of hydrocarbons—including, in particular, coal bed methane—constitute mining ownership regardless of the place of their occurrence. The deposits of hard coal, methane as an associated mineral, lignite,

metal ores, excluding bog iron ores, native metals, radioactive ores, native sulfur, rock salt, sylvinit, potassium-magnesium salts, gypsum and anhydrite, precious stones, rare-earth elements, noble gases, as well as the deposits of curative water, thermal water, and brine are covered by mineral rights wherever they occur. Mineral rights are exercised solely by the State Treasury. Under the provisions of legal acts, the State Treasury may, to the exclusion of other persons, use the object of the mineral rights or dispose of its rights solely by establishing a mining usufruct which shall be established by way of an agreement in writing. In light of the said Act, the activity consisting in the prospection, exploration, and production of hydrocarbon deposits may be carried on exclusively after obtaining a concession. Due to the character of the State Treasury, the entitlements of the State Treasury provided by mineral rights with respect to the above activities are exercised by competent concession-granting authorities, i.e., bodies entitled by law to grant decisions on the basis of which it is possible to undertake an activity which requires a concession. According to the legislator, the prospection of hydrocarbon deposits means performing geological development works with a view to establishing and preliminarily documenting the existence of a deposit. The exploration of hydrocarbon deposits means carrying out geological development works in the area of preliminarily documented hydrocarbon deposits. The extraction of hydrocarbons from deposits means conducting the hydrocarbon extraction, as well as preparing the extracted hydrocarbons for transport and their transport within the area of a mining plant. The legislator devoted a separate chapter in the Act on Geological and Mining Law to provide regulations concerning the issue of granting concessions for the prospection, exploration, and production of hydrocarbon deposits (Act on Geological and Mining Law, Chapter III). The procedure of applying for concessions for the prospection, exploration, and production of hydrocarbon deposits, unlike in the case of other concessions, is preceded by an eligibility procedure to assess the ability of the interested entity to carry out the activities in the scope of the prospecting for and exploration of hydrocarbon deposits and the extraction of hydrocarbons from deposits. Within the framework of the eligibility procedure that is carried out by the Minister of the Environment, it is determined whether the entity intending to apply for a concession for the prospecting for and exploration of a hydrocarbon deposit and the extraction of hydrocarbons from a deposit, or a concession for the extraction of hydrocarbons from a deposit, remains under corporate control of a third-party state, entity, or citizen of a third-party state, and, if so, if such control can pose a threat to national security. In such a case, a third-party state is understood to be any state other than a Member State of the European Union, Member State of the European Free Trade Agreement (EFTA), or a Member State of the North Atlantic Treaty Organization. Corporate control is interpreted as all forms of obtaining, directly or indirectly, entitlements, which, separately or jointly, given all legal and factual circumstances, make it possible for the entity to exert decisive influence on the entity interested in conducting activities within the scope of prospecting for and exploration of a hydrocarbon deposit and the extraction of hydrocarbons from a deposit or a concession for the extraction of hydrocarbons from a deposit. An example of circumstances that enable to exert influence on the entity interested in conducting said activities is the case where the said entity holds, directly or indirectly, a majority of votes at the general meeting or is entitled to appoint or dismiss a majority of the members of the management board or supervisory board. The aforementioned eligibility procedure is conducted upon the application of the entity interested in conducting activities within the scope of prospecting for and exploration of a hydrocarbon deposit and the extraction of hydrocarbons from a deposit or a concession for the extraction of hydrocarbons from a deposit. The legislator requires from the minister responsible for the environment to keep a list of the entities to which a decision on the positive assessment in the eligibility procedure has been issued. It should be underlined that the decision on the positive assessment in the eligibility procedure constitutes a mandatory prerequisite that entitles the entity to which it has been issued to submit a tender in the tender procedure for obtaining a concession to prospect for and explore hydrocarbon deposits and to extract hydrocarbons from deposits or a concession to extract hydrocarbons from deposits. A concession to prospect for and explore hydrocarbon deposits and to extract hydrocarbons from deposits or a concession to extract hydrocarbons from deposits may be granted by way of a tender procedure but also upon the request of

the interested entity. The tender procedure should have an objective and nondiscriminatory character, and it should give priority to the best systems of prospecting for and the exploration of hydrocarbon deposits or the extraction of hydrocarbons from deposits.

The legislator cautioned that the tender procedure should be based on the following criteria:

- (1) experience in the activity concerning the prospecting for and the exploration of hydrocarbon deposits or the extraction of hydrocarbons from deposits in order to ensure the safety of the conducted activities in terms of the protection of human and animal life and health, as well as the protection of the environment;
- (2) technical capabilities to carry out the activity in the scope of prospecting for and the exploration of hydrocarbon deposits and the extraction of hydrocarbons from deposits or the extraction of hydrocarbons from deposits, respectively, and, in particular, having relevant technical, organizational, logistics, and staff resources, including the cooperation in the development and implementation of innovations in prospecting for, exploring, and extracting hydrocarbons from deposits with scientific institutions dealing with the exploration of the geological structure of Poland, as well as analytics, technology, and methodology of prospecting for deposits that take into consideration the specificity of Polish geological conditions and apply to these conditions;
- (3) financial capabilities providing due guarantee of performing the activity of prospecting for and the exploration of hydrocarbon deposits and the extraction of hydrocarbons from deposits or the extraction of hydrocarbons from deposits, respectively, and, in particular, the sources and manners of financing the intended activities, including the share of own funds and funds originating from third-party capital;
- (4) proposed technology of performing geological development works, including geological works or mining works;
- (5) scope and schedule of the proposed geological development works, including geological works or mining works; and
- (6) scope and schedule of the obligatory sampling resulting from geological works, including drilling cores.

The amount of the fee for the establishment of the mining usufruct, due at the stage of prospecting and exploring, may constitute an additional criterion when two or more tenders submitted by the entities interested in prospecting for and the exploration of hydrocarbon deposits or the extraction of hydrocarbons from deposits obtain the same score.

The concession for prospecting for and the exploration of a hydrocarbon deposit and the extraction of hydrocarbons from a deposit or the concession for the extraction of hydrocarbons from a deposit should define at least the following issues:

- (1) the type and the manner of performing the indented activity;
- (2) the area within which the intended activity is to be pursued;
- (3) the period of the concession validity;
- (4) the date of the commencement of the activities covered by the concession and the specific conditions—in particular, those pertaining to public safety and health, environmental protection, or rational management of the deposit;
- (5) the boundaries of the mining district and mining area; and
- (6) the minimum degree of the utilization of the deposit resources and the measures necessary for the purpose of the rational management of the deposit.

The concession to prospect for, to explore hydrocarbon deposits, and to extract hydrocarbons from deposits is granted for a fixed period; however, not shorter than 10 years and not longer than 30 years. Under the provisions of the concession, the entrepreneur is granted an exclusive right to carry out the activities covered with the concession in the area defined therein. In addition, the concession granting authority concludes a mining usufruct agreement with the entity.

It is worth noting that one of the obligations imposed by the legislator on the entrepreneur who has been granted the concession for prospecting for, exploring hydrocarbon deposits, and extracting hydrocarbons from deposits is to provide the state geological service with current parameters of the extraction of hydrocarbons from the deposit and to notify the concession granting authority of such communication.

4. Results and Discussion

4.1. The Estimation of Coal Bed Methane Resources

The first of the selected prospective areas is located between the fault zone of Żory-Suszec-Jawiszowice in the North and the fault zone of Bzie-Czechowice in the South of Poland. Within the boundaries of the designated area, there are the undeveloped deposits Warszowice-Pawłowice Północ and Pawłowice-rej, the sub-marginal deposits Studzionki-Mizerów and the Southern section of the Kobiór-Pszczyna deposit. The region is considered to be relatively well-recognized in terms of methane conditions. The fact that, within the said region, there occur CBM resources in the zone of secondary methane accumulation estimated at 5.18 billion Nm^3 that constitutes an additional argument in favor of regarding the region as the most promising one [38]. Sixty-five wells are located in the area; the wells were used to make tests concerning the methane content of the seams by means of a one-phase vacuum degassing in the so-called ball containers, a method designed by Katowice Geological Company (*Katowickie Przedsiębiorstwo Geologiczne*). Another eight wells located in the same region were used to perform the tests of free desorption using the US Bureau of Mine (USBM) method developed in the United States, which enables to measure the content of residual methane and to estimate the volume of desorbable methane. The roof of the basic zone of methane bearing seams (the roof of the series) of methane content $>4.5 \text{ m}^3/\text{Mg}_{\text{daf}}$ is deposited at the depth of approximately 750 m in the East up to the depth of 1200 m in the region of the Pawłowice deposit. The estimated recoverable reserves in the first area (Figure 5) are presented in Table 5.

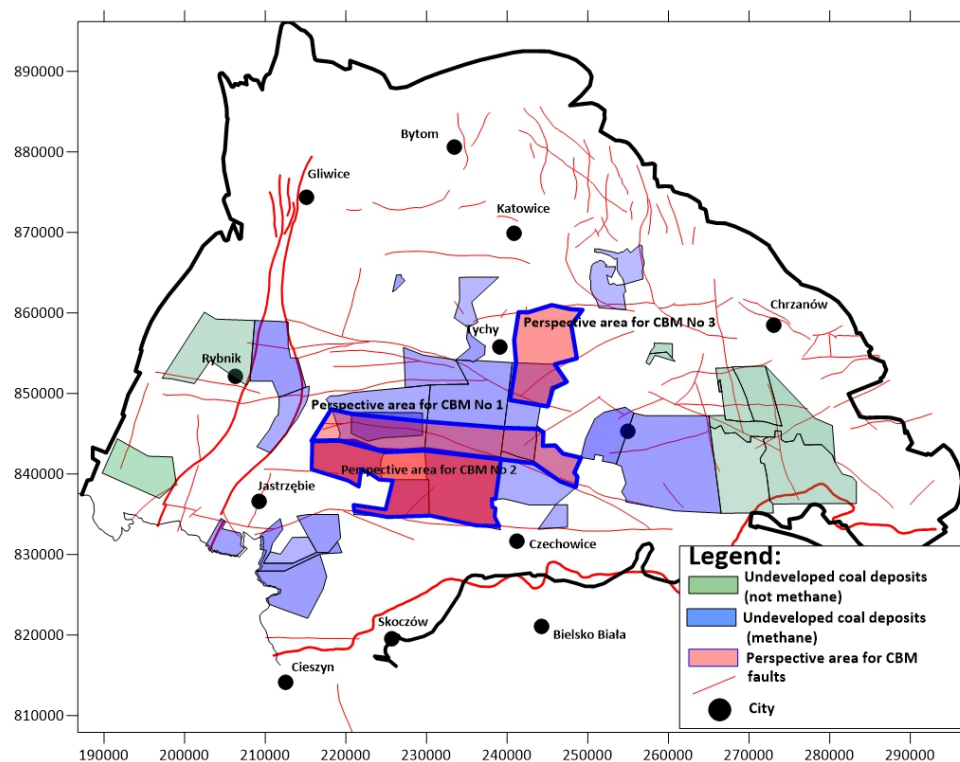


Figure 5. Prospective regions in terms of methane production using directional drilling from the surface set against the undeveloped areas of the Upper Silesian Coal Basin.

Table 5. Recoverable reserves of CBM considered as the main mineral in the first prospective region.

Calculation Interval (Depth, M)	Recoverable Reserves of CBM Considered as the Main Mineral (Million Nm ³)
From the roof of the zone to 1000 m	1050.3
1000–1250 m	8361.6
1250–1500 m	7831.4
Total	17,243.3

In Tables 5–7, methane resources were estimated according to the volumetric method (GIP, Gas-In-Place) in the adopted intervals for estimating resources (a) from the roof of the zone to 1000 m, (b) 1000–1250 m, and (c) 1250–1500 m for three perspective areas taking into account the following boundary conditions: depth 1500 m, thickness of coal seams >0.6 m, and methane capacity >4.5 m³/Mg_{daf}.

Table 6. Recoverable reserves of CBM considered as the main mineral in the second prospective region.

Calculation Interval (Depth, M)	Recoverable Reserves of CBM Considered as the Main Mineral (Million Nm ³)
From the roof of the zone to 1000 m	2674.4
1000–1250 m	4034.8
1250–1500 m	5738.1
Total	12,447.4

Table 7. Recoverable reserves of CBM considered as the main mineral in the third prospective region.

Calculation Interval (Depth, M)	Recoverable Reserves of CBM Considered as the Main Mineral (Million Nm ³)
From the roof of the zone to 1000 m	28.4
1000–1250 m	1123.7
1250–1500 m	2734.9
Total	3887.0

The second prospective area is located in the hanging wing of the fault zone Żory-Suszc-Jawiszowice (Figure 5). The area encompasses the Międzyrzecze deposit and the Southern section of the Studzienice deposit, as well as the Central section of the Kobiór-Pszczyna deposit. The region is considered to be most prospective in the Eastern part (Międzyrzecze deposit), which is indicated by a considerable dynamic of methane desorption. There are 35 wells located in the area to perform tests concerning the methane content of the seams by means of the above-described method developed by the Katowice Geological Company and another four wells to perform the tests using the USBM method. The roof of the zone lies at depths of the order of 750–1000 m. The estimated recoverable reserves in the second prospective area are compiled in Table 6.

The third selected prospective area encompasses the documented CBM deposit Łędziny and the Northern section of the Studzienice deposit (Figure 5). There are 15 wells located in the area to perform tests concerning the methane content of the seams by means of the method developed by the Katowice Geological Company and another three wells to perform the tests using the USBM method. The roof of the CBM zone lies at the depth interval ranging from 950 to over 1100 m.

The estimated recoverable reserves in the third prospective area are shown in Table 7.

4.2. Numerical Simulation of CBM Extraction

In all of the simulation scenarios examined, hydraulic fracturing combined with directional drilling and casing string perforation was applied. The purpose of the casing string perforation was to achieve the maximum production rate of the well. The particular scenarios differed in terms of the

hydraulic fracturing. For all of the production wells, hydraulic fracturing simulations were carried out for a number of depth intervals within the period of six to eight months from the commencement of the injection.

During the first six months, it was clearly observed for each of the simulations that, predominantly, water was produced from the seams. In this period, it was found that the rock mass pressure decreases, which is caused by water production from the seam. The process prompts methane desorption from the coal matrix. The simulation covered the period of five years; the daily production rates of methane and water are presented in Figure 6. The simulated methane extractions from seams 333, 336, and 337 are facilitated by means of horizontal wells in particular seams—Studzienice 1H, Studzienice 2H, and Studzienice 3H, respectively. The Studzienice 5V well performs the function of monitoring the depth of the coal seam deposition and, thus, constitutes a benchmark for the horizontal wells. Due to the low value of coal seams' permeability of the analyzed deposit, a multilateral production well was used in the model.

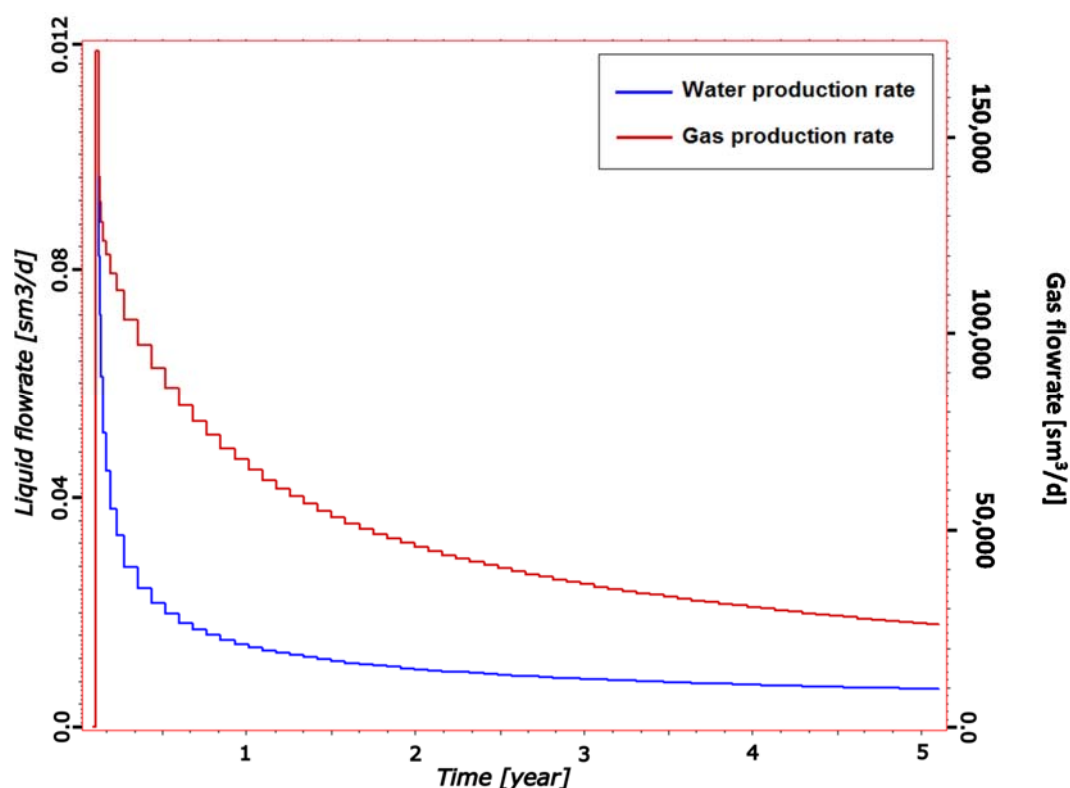
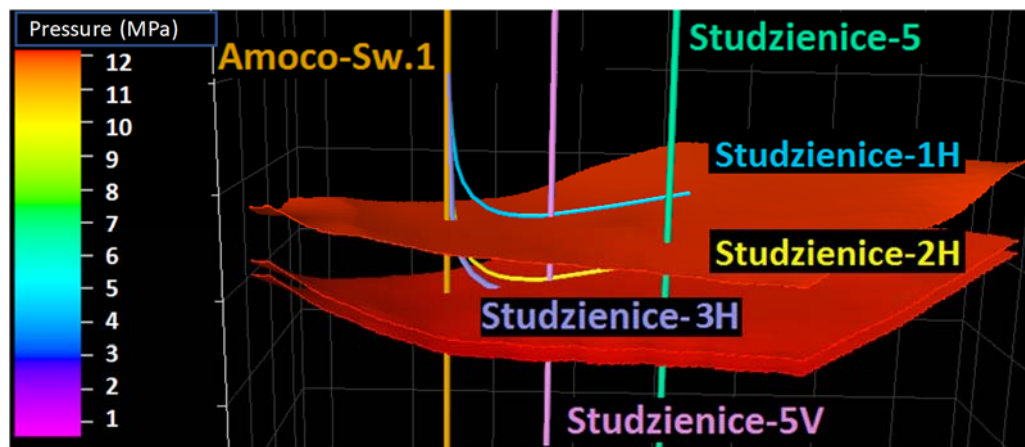


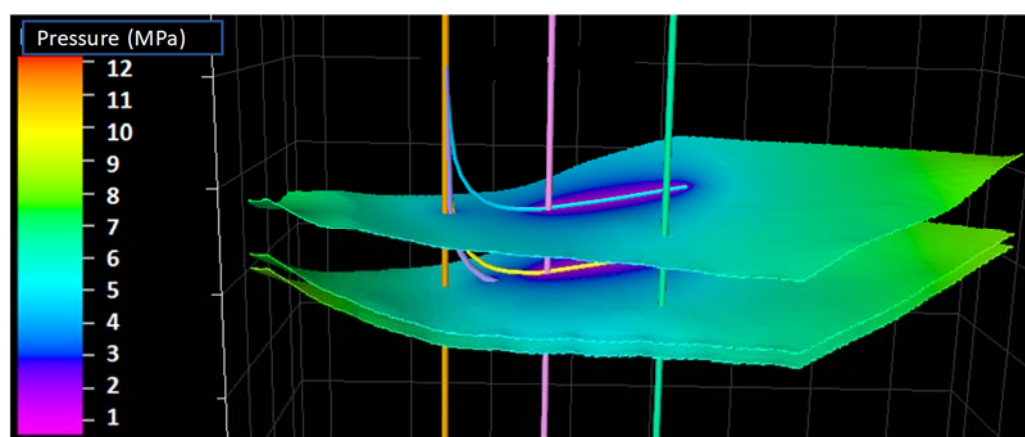
Figure 6. Daily production rates of water and methane during the simulated extraction of CBM for the entire model of the deposit using three directional wells.

Multilateral directional drilling is a technology developed and applied for the first time in the United States in order to improve the production flow and increase the efficiency of production rates of single wells. The system of branched multilateral wells drilled into the coal seam facilitates the extraction of approximately 85%–90% of gas contained in a 5-km² play over a period of about 30 months [39]. So far, the systems of branched multilateral wells have been successfully applied in the development of CBM technology in Alberta Basin, Canada and San Juan Basin, the United States, as well as in Bowen/Sydney Basin, Australia [40–43]. Branched multilateral wells constitute an effective solution to achieve high production rates of the CBM extraction process. The application of the system of branched multilateral wells is beneficial for the CBM technology due to the larger extent of drainage zone. Moreover, such a system enables to achieve the maximum rate of methane production in a relatively short time, along with the decrease in water drainage from the coal seam [44].

Figure 7 presents the distribution of multilateral wells in the simulation model and the changes in the distribution of coal seam pressure during the simulation of methane extraction. The considerable decrease in the rock mass pressure was caused by the extraction of water and methane from the coal seams.



(a)



(b)

Figure 7. Distribution of pressure in coal seams (a) before the simulation and (b) after 5 years of methane extraction (end of the simulation).

For the assumed parameters of the deposit, the aggregate methane production rate from coal seams 333, 336, and 337 totaled approximately 76.2 million Nm^3 . The rates of methane production for the particular horizontal wells are presented in Table 8, whereas Figure 8 shows the comparison of the aggregate methane production rate in the wells during the simulation.

Table 8. Rates of methane production for the particular wells.

Production Well	Methane Production Rate (Nm^3)
Studzienice-1H	23,633,812
Studzienice-2H	27,043,441
Studzienice-3H	25,513,001
Total	76,190,254

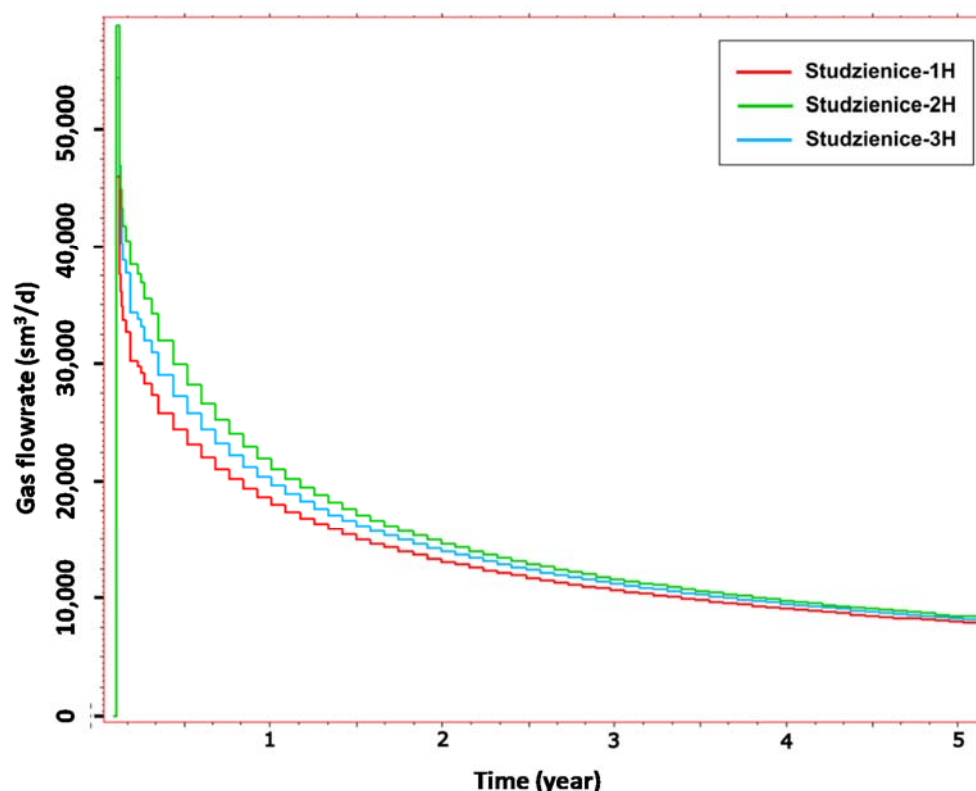


Figure 8. The comparison of the changes in methane production rates in the particular wells.

The results of the numerical simulations demonstrate that the aggregate volume of methane extracted from three coal seams totals 76.2 million Nm^3 in the five-year period of the simulation. Due to the low permeability of coal in the deposit (the assumed coal permeability in the numerical model equals 1.5 mD), the technology of multilateral wells was decided to be incorporated into the simulation model. The aggregate methane production rate for each of the branches of the multilateral well—in particular, coal seams—was in the range of 23.6–27.0 million Nm^3 , whereas the average daily methane production rates ranged from 12,900 to 14,800 thousand Nm^3/d . The obtained results of the numerical simulations can be compared with the results of experimental works carried out in the Upper Silesian Coal Basin in the period of 2016–2018 within the framework of a research project Geo-Metan [45,46]. Geo-Metan was a pilot project executed in the area of an undeveloped coal deposit Międzyrzecze whose main objective was the development and refinement of Polish technologies of CBM exploration and pre-mining extraction. Within the test phase, which covered the period of 145 days, the directional well drilled into a coal seam of 0.2–0.8-mD permeability achieved a maximum flow of methane of 10,000 Nm^3/d after a hydraulic fracturing procedure was applied. With the completion of water drainage, the daily production rate of methane stabilized at the level of approximately 5000 Nm^3/d . The lower values of the daily production rates achieved in the experimental works, as compared to the results of numerical simulations, may be caused by different reservoir parameters of the analyzed deposits, especially coal permeability.

5. Conclusions

The paper presents the assessment of the resources of methane considered as the main mineral in the most prospective selected areas of the Upper Silesian Coal Basin, Poland in the region of undeveloped deposits. The methane resources were estimated by means of the volumetric method (GIP) at three depth levels—1000, 1250, and 1500 m.

Three areas of the Upper Silesian Coal Basin were selected as the most prospective in terms of methane resources. The analysis allowed assessing the distribution of CBM resources in the vertical

profile in the adopted intervals for estimating resources: (a) from the roof of the zone to 1000 m, (b) 1000–1250 m, and (c) 1250–1500 m for three prospective areas.

The total recoverable reserves of CBM considered as the main mineral in the first prospective region equal 17,243.3 million Nm^3 , in the second region—12,447.4 million Nm^3 , and in the third region—3887 million Nm^3 . The Studzienice deposit was selected for the numerical modeling of CBM extraction. A structural parameter model of the coal-bearing Upper Carboniferous formations was developed, and the reservoir parameters were analyzed. The static model was supplemented with detailed reservoir parameters, as well as the thermodynamic properties of reservoir gases and fluids. Next, numerical simulations of methane extraction from the selected seams were carried out.

The above analyses were possible to perform by means of ECLIPSE software with the CBM option. The software compatibility with the petrel reservoir engineering package enabled to simulate the process of CBM extraction. The results concerning the changes in the average rock mass pressure during the simulated methane extraction were presented. The findings concerning the efficiency of a multilateral well system extracting methane from three selected coal seams were discussed.

The total resources of methane in the area amounted to approximately 446.5 million Nm^3 . Based on the simulations, it was concluded that, in the first six months, water is produced from the seams, which is connected with the decrease in the rock mass pressure. The process prompts methane desorption from the coal matrix, which, in turn, results in a total methane production of 76.2 million Nm^3 within the 5five-year period of the simulations, which constitutes about 17% of total methane resources (GIP).

The results of numerical simulations confirm that the application of multilateral well systems combined with hydraulic fracturing considerably improves the efficiency of CBM extraction from seams characterized by low coal permeability. In comparison with the conventional wells, the multilateral well systems provide the possibility of optimizing the economic and technical performance of CBM extraction. In addition, the paper also presents an in-depth analysis of Polish legislation concerning the activities aimed at prospecting, exploring, and extracting the deposits of hydrocarbons in light of the binding regulations stipulated by the Act on Geological and Mining Law.

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References

1. Levine, J.R. Generation, storage and migration of natural gas in coal bed reservoirs. *Alta. Res. Counc. Inf. Ser.* **1990**, *109*, 84–130.
2. Seidle, J. *Fundamentals of Coalbed Methane Reservoir Engineering*; PennWell Books: Tulsa, OK, USA, 2011.
3. Chattaraj, S.; Mohanty, D.; Kumar, T.; Halder, G. Thermodynamics, kinetics and modeling of sorption behaviour of coalbed methane—A review. *J. Unconv. Oil Gas Resour.* **2016**, *16*, 14–33. [[CrossRef](#)]
4. Wojtacha-Rychter, K.; Smolinski, A. A study of dynamic adsorption of propylene and ethylene emitted from the process of coal self-heating. *Sci. Rep.* **2019**, *9*, 18277. [[CrossRef](#)] [[PubMed](#)]
5. Wojtacha-Rychter, K.; Howaniec, N.; Smoliński, A. The effect of coal grain size on the sorption of hydrocarbons from gas mixtures. *Int. J. Energy Res.* **2019**, *43*, 3496–3506. [[CrossRef](#)]
6. Wojtacha-Rychter, K.; Smoliński, A. Selective adsorption of ethane, ethylene, propane, and propylene in gas mixtures on different coal samples and implications for fire hazard assessments. *Int. J. Coal Geol.* **2019**, *202*, 38–45. [[CrossRef](#)]
7. Kuuskraa, V.A.; Stevens, S.H. *Worldwide Gas Shales and Unconventional Gas: A Status Report*; American Clean Skies Foundation (ACSF): Washington, DC, USA; Research Partnership to Secure Energy for America (RPSEA): Houston, TX, USA, 2009.

8. Thomas, L. *Coal Geology*, 2nd ed.; Wiley-Blackwell: Oxford, UK, 2013.
9. Hadro, J.; Spińczuk, A.; Chećko, J. *Ocena Potencjału Zasobowego MPW dla Pokładów Węgla Zalegających w strefie Wtórno Nagromadzenia Metanu Sorbowanego Południowej Części Niecki Głównej*; CAG Państwowy Instytut Geologiczny: Warszawa, Poland, 2004.
10. Reeves, S. Unconventional gas resources to reserves—A predictive approach. In Proceedings of the AAPG Rocky Mountain Geology & Energy Resources Conference, Denver, Colorado, 9–11 July 2008.
11. Petroleum Resource Management System (PRMS). Society of Petroleum Engineers/American Association of Petroleum Geologists/World Petroleum Council/Society of Petroleum Evaluation Engineers. 2007. Available online: www.spe.org (accessed on 1 April 2020).
12. Regulation of the Minister of Environment, 2015; item 968; The Regulation of 10 July 2015; Journal of Laws of 2015. Available online: <http://prawo.sejm.gov.pl/isap.nsf/download.xsp/WDU20150000968/O/D20150968.pdf> (accessed on 1 April 2020).
13. Jureczka, J. Pre-mining methane extraction and capture from coal seams by using surface boreholes in the “Mysłowice Wesola” hard coal mine project—Progress and initial assessment of works. *Bezpieczeństwo Pracy i Ochr. Środowiska w Górnictwie* **2014**, *12*, 21–26.
14. Wojtacha-Rychter, K.; Smoliński, A. Multi-component gas mixture transport through porous structure of coal. *Fuel* **2018**, *233*, 37–44. [[CrossRef](#)]
15. Wojtacha-Rychter, K.; Smoliński, A. The interactions between coal and multi-component gas mixtures in the process of coal self-heating at different various temperatures ranges: An experimental study. *Fuel* **2018**, *213*, 150–157. [[CrossRef](#)]
16. McCants, C.Y.; Spafford, S.; Stevens, S.H. Five-spot production pilot on tight spacing: Rapid evaluation of a coalbed methane block in the Upper Silesian Coal Basin, Poland. In Proceedings of the 2001 International Coalbed Methane Symposium, Tuscaloosa, AL, USA, 14–18 May 2001; pp. 193–204.
17. Shen, R.; Qiao, L.; Fu, L.; Yang, H.; Shi, W. Research and Application of Horizontal Drilling for CBM. *Soc. Pet. Eng.* **2012**. [[CrossRef](#)]
18. He, Z.; Jun-cheng, L.; Zhi-jun, Z.; Wei, L. Research on Safety Monitoring System of Bottom Hole Pressure in Coalbed Methane Underbalanced Drilling Process. *Open Fuels Energy Sci. J.* **2015**, *8*, 197–201. [[CrossRef](#)]
19. Palmer, I. Coalbed methane completions: A world view. *Int. J. Coal Geol.* **2010**, *82*, 184–195. [[CrossRef](#)]
20. Kotas, A.; Kwarciniński, J.; Jureczka, J. *Calculation of Methane Resources in Coal Seams of the Upper Silesian Coal Basin*; Narodowe Archiwum Geologiczne PIG-PIB: Warszawa, Poland, 1990.
21. Ayers, W.B., Jr. Coalbed gas systems, resources, and production and a review of contracting cases from the San Juan and Powder River basins. *Am. Assoc. Pet. Geol. Bull.* **2002**, *86*, 1853–1890.
22. Pekała, Z. Occurrence of methane in the Upper Silesian Coal Basin against the background of the general geological structure of the area. *Biul. Inf. Geol.* **1992**, *1*, 8.
23. Kaziuk, H.; Bromek, T.; Chećko, J.; Chudzicka, B. Conditions of coal seams methane in the Upper Silesian Coal Basin and its resources. In Proceedings of the International Conference on the Use of Coal Bed Methane, Katowice, Poland, 5–7 October 1994.
24. Zhang, M.; Yang, Y.; Xia, Z.; Cui, Z.; Ren, B.; Zhang, W.; Lau, H.C. Best Practices in Static Modelling of a Coalbed Methane Field: An Example from the Bowen Basin in Australia. *Soc. Pet. Eng.* **2014**. [[CrossRef](#)]
25. Zhou, F.; Yao, G.; Tyson, S. Impact of geological modeling processes on spatial coal bed methane resource estimation. *Int. J. Coal Geol.* **2015**, *146*, 14–27. [[CrossRef](#)]
26. Sinayuc, C.; Shi, J.Q.; Imrie, C.E.; Syed, S.A.; Korre, A.; Durucan, S. Implementation of horizontal well CBM/ECBM technology and the assessment of effective CO₂ storage capacity in a Scottish coalfield. *Energy Procedia* **2011**, *4*, 2150–2156. [[CrossRef](#)]
27. Galas, C.; Savenko, V.; Kieke, D.E. *Simulation Study of Methane and Carbon Dioxide Migration and Leakage during Normal and Enhanced Field Operations to Recover Coal Bed Methane from Coal Seams*; Carbon Dioxide Capture for Storage in Deep Geologic Formations; Eide, L.I., Ed.; CPL Press: Totnes, UK, 2009; Volume 3.
28. Anggara, F.; Sasaki, K.; Amijaya, H.; Sugai, Y.; Setijadji, L.D. CO₂ injection in coal seams, an option for geological CO₂ storage and enhanced coal bed methane recovery (ECBM). In Proceedings of the Indonesian Petroleum Association, Thirty-Fourth Annual Convention & Exhibition, Jakarta, Indonesian, 18–20 May 2010.
29. Jureczka, J.; Chećko, J.; Krieger, W.; Kwarciniński, J.; Urych, T. Prospects for geological storage of CO₂ with enhanced coal bed methane recovery in the Upper Silesian Coal Basin. *Biul. Państwowego Inst. Geol.* **2012**, *448*, 117–131.

30. Chećko, J.; Urych, T.; Magdziarczyk, M.; Smoliński, A. Research on the Processes of Injecting CO₂ into Coal Seams with CH₄ Recovery Using Horizontal Wells. *Energies* **2020**, *13*, 416. [\[CrossRef\]](#)
31. Koteras, A.; Checko, J.; Urych, T.; Magdziarczyk, M.; Smolinski, A. An Assessment of the Formations and Structures Suitable for Safe CO₂ Geological Storage in the Upper Silesia Coal Basin in Poland in the Context of the Regulation Relating to the CCS. *Energies* **2020**, *13*, 195. [\[CrossRef\]](#)
32. Kwarciański, J. *Weryfikacja Bazy Zasobowej Metanu Pokładów Węgla Jako Kopaliny Głównej Na Obszarze Górnośląskiego Zagłębia Węglowego*; Narod. Arch. Geol. PIG-PIB: Warszawa, Poland, 2006.
33. *ECLIPSE Reservoir Simulation Software*; Simulation Software Manuals 2011.1; Schlumberger: Houston, TX, USA, 2011.
34. *Petrel Seismic-to-Simulation Software*; Version 2010.1; Schlumberger: New York, NY, USA, 2010.
35. Arri, L.E.; Yee, D.; Morgan, W.D.; Jeanson, N.W. Modeling Coalbed Methane Production with Binary Gas Sorption. In Proceedings of the SPE Rocky Mountain Regional Meeting, Casper, Wyoming, 18–21 May 1992.
36. Wageningen, W.F.C.; Maas, J.G. Reservoir simulation and interpretation of the RECOPOL ECBM pilot in Poland. In Proceedings of the International Coalbed Methane Symposium, Tuscaloosa, AL, USA, 23–24 May 2007.
37. Reeves, S.; Taillefert, A. *Reservoir Modeling for the Design of the RECOPOL CO₂ Sequestration Project, Poland*; Topical Report; Advanced Resources International: Washington, DC, USA, 2002.
38. Hadro, J.; Wójcik, I. Metan pokładów węgla: Zasoby i eksploatacja. *Przegląd Geol.* **2013**, *61*, 13–15.
39. Wight, D. Unconventional drilling methods for unconventional reservoirs. *Houston Geol. Soc. Bull.* **2006**, *48*, 41.
40. Moore, T.A. Coalbed methane: A review. *Int. J. Coal Geol.* **2012**, *101*, 36–81. [\[CrossRef\]](#)
41. Gentzis, T.; Goodarzi, F.; Cheung, F.K.; Laggoun-Défarge, F. Coalbed methane producibility from the Mannville coals in Alberta, Canada: A comparison of two areas. *Int. J. Coal Geol.* **2008**, *74*, 237–249. [\[CrossRef\]](#)
42. Ham, Y.S.; Kantzas, A. Development of coalbed methane in Australia: Unique approaches and tools. In Proceedings of the CIPC/SPE Gas Technology Symposium 2008 Joint Conference, Calgary, AB, Canada, 16–19 June 2008.
43. Ren, J.; Zhang, L.; Ren, S. Multi-branched horizontal wells for coalbed methane production: Field performance and well structure analysis. *Int. J. Coal Geol.* **2014**, *131*, 52–64. [\[CrossRef\]](#)
44. Chen, S.; Tang, D.; Tao, S.; Yang, Y.; Chen, L. Current status and key factors for coalbed methane development with multibranch horizontal wells in the southern Qinshui basin of China. *Energy Sci. Eng.* **2019**, *7*, 1572–1587. [\[CrossRef\]](#)
45. Jureczka, J.; Hadro, J.; Kroplewski, Ł. Gilowice Project as a First Step to Develop Pre-Mine Drainage Technology in Poland—Update on Activities, Review of the Latest Results. XXVIII School of Underground Mining, Session—Coal Mine Methane as a Valuable Energy Source. Krakow. 27 February 2019. Available online: <https://www.pgi.gov.pl/dokumenty-przeglądarka/publikacje-2/biuletyn-pig/biuletyn-448/1240-biul448-1-11jureczka/file.html> (accessed on 1 April 2020).
46. Polskie Górnictwo Naftowe i Gazownictwo (PGNiG). Coal-bed methane-fueled power generation unit launched by PGNiG in Gilowice. 2019. Available online: <http://en.pgnig.pl/news/-/news-list/id/coal-bed-methane-fueled-power-generation-unit-launched-by-pgnig-in-gilowice/newsGroupId/1910852> (accessed on 1 April 2020).

