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# Extraction Study of Lignite Coalbed Methane as a Potential Supplement to Natural Gas for Enhancing Energy Security of Western Macedonia Region in Greece

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**Abstract:** Greek lignite reserves are mainly located in the northwestern part of the country (Region of Western Macedonia, Greece), reaching a total of 5 billion tons. Considering that Greece is planning to stop burning lignite for electricity production, the recovery of the $CH_4$ trapped in lignite coalbed reservoirs can be a valuable alternative for power generation and may help to reduce the direct emissions of methane during mining activities. The aim of the present study was to evaluate the LCBM in the Region of Western Macedonia, Greece (Ptolemaida basin). In order to assess the LCBM that could be extracted, three samples were collected from an active mine and were subjected to desorption experiments at different temperatures (25 °C, 50 °C, 100 °C, and 150 °C) by channeling high purity Ar gas at 1 atm of pressure. According to the results, the highest amount of $CH_4$ was extracted during the desorption process at 50 °C, while the total amount of $CH_4$ from all three samples was 0.82 $m^3$/kg, confirming the presence of $CH_4$ in the lignite deposits. Finally, a SWOT analysis was carried out that shows the strengths and opportunities against the weaknesses and threats of a potential LCBM exploitation in Greece, while also taking into account the social, economic, and environmental nexus.

**Keywords:** energy transition; lignite coalbed methane; extraction; desorption; Region of Western Macedonia–Greece



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## 1. Introduction

The continuous growth of the global economy and population has led the global energy system to face the greatest challenges and uncertainties for almost 50 years. The primary energy demand increased by 5.8% in 2021, keeping the consumption of fossil fuels unchanged, while in the period from 2019 to 2021, renewable energy increased by 8 exajoules (EJ). Table 1 shows the global primary energy consumption, measured in EJ, according to the latest published data by the BP Statistical Review of World Energy [1], with crude oil and natural gas being the main suppliers. The demand for natural gas is forecasted to increase by 40% from 2016 to 2040, which requires the production of more unconventional gas to globally cover the needs. Currently, less than 15% of the recoverable resources of natural gas has been exploited [2]. Unconventional gas resources such as coalbed methane, tight gas, and shale gas comprise 45% of the remaining natural gas resources, since the possible reserves in the world are estimated to be 184,200 trillion cubic feet [3].

Coalbed methane (CBM), which is extracted from underground coal, is considered as a major unconventional resource of natural gas, being recognized by today's oil and gas industry as a potential combustion fuel for power generation and industrial applications. Considering the growing environmental concerns, power generation using cleaner technologies such as the conversion of methane from coal mines into $CO_2$ and water could significantly reduce greenhouse gases, earning carbon credits, and other pollutants (e.g., sulfur and mercury), as compared to the use of coal-fired power generation technology. Therefore, natural gas is preferred for power generation in European countries as a low-carbon alternative to coal, since natural gas plays a key role in the pathway to lower $CO_2$ emissions [4]. As a matter of fact, $CO_2$-equivalent emissions from energy, industrial processes, methane, and flaring rose 5.7% globally in 2021 to 39.0 $GtCO_2e$ (Table 1). Carbon dioxide-equivalent emissions through oil-, gas-, and coal combustion-related activities rose 5.9% globally in 2021 to 33.9 $GtCO_2e$, while natural gas flaring corresponds to 0.153 $GtCO_2e$ [1]. Hence, as economic growth will continue to drive $CO_2$ emissions through to 2040, the switch to lower-emission fuels, as imposed by the EU energy and climate policy [5], will help substantially to moderate emissions and reduce the carbon footprint.

**Table 1.** Primary energy consumption, consumption by fuel, and carbon dioxide-equivalent emissions [1].

| Stated for 2021 | Primary Energy Consumption (EJ) | Oil Consumption (EJ) | Coal Consumption (EJ) | Natural Gas Consumption (EJ) | Renewable Energy Consumption (EJ) | $CO_2$ Emissions ** ($GtCO_2e$) |
|---|---|---|---|---|---|---|
| North America | 113.7 | 42.1 | 11.3 | 37.2 | 8.4 | 6.2 |
| S. and Cent. America | 28.5 | 11.3 | 1.46 | 5.88 | 3.4 | 1.5 |
| Europe | 82.4 | 27.6 | 10.0 | 20.6 | 10.1 | 4.0 |
| Middle East | 37.8 | 16.3 | 0.34 | 20.7 | 0.18 | 2.7 |
| Africa | 20.0 | 7.86 | 4.21 | 5.9 | 0.47 | 1.7 |
| Asia–Pacific | 272.5 | 70.65 | 127.6 | 33.1 | 17.2 | 20.0 |
| CIS * | 40.3 | 16.3 | 0.34 | 20.7 | 0.18 | 2.7 |
| Total World | 595.2 | 184.2 | 160.1 | 145.4 | 39.9 | 39.0 |

* Commonwealth of Independent States, ** sum of $CO_2$-equivalent emissions from energy, flaring, methane emissions, and industrial processes.

In countries, such as the U.S.A. and Canada, with extensive coal basins, the CBM-to-gas conversion process has become, since 1970, a viable sustainable energy source for household and industrial uses. Recoverable coal reserves can be found abundantly in many locations throughout the world, such as in the U.S.A, Russia, China, Australia, and India [6]. The distribution of CBM resources in the world shows that the former Soviet Union is leading with $113.0 \times 10^{12}$ $m^3$, followed by North America with $85.4 \times 10^{12}$ $m^3$, and the Asia–Pacific with $48.8 \times 10^{12}$ $m^3$, while Europe follows with $7.7 \times 10^{12}$ $m^3$ [3]. However, in many coal-rich countries such as China, India, and others, CBM is a fairly new term due to the time incurred by companies for exploring, developing, and extracting CBM gas from its reservoir. It has been estimated that the drill holes needed for CBM exploration are 10 times more than those needed for natural gas [4]. On the one hand, CBM must be removed from underground coal, since it is not allowed to be vented into the atmosphere due to its greenhouse effect as well as due to its potential explosion risk in coal mines [7].

Coalbed methane (CBM) is generally formed in shallow coal deposits, where different types of gases (including methane) are produced [8]. CBM reservoirs are fast-growing reservoirs in which the methane produced is stored mainly through adsorption on the coal matrix surface (such as micropores). Coal, having a moderate intrinsic porosity, can store about six times more gas than sandstones of an equivalent volume. However, the gas storage capacity and methane generation are functions of coal rank and pressure. Therefore, of the coal ranks, anthracite has the greatest storage capacity, followed by bituminous and subbituminous coals, and lignite [6]. Methane is generated in low-rank coals, such as lignite, through microbial activity [9] and in higher-rank coals, such as anthracite, during the thermal maturation of their organic compounds [10]. The generated methane is adsorbed on the surface of the organic materials that make up the coal, while the coal's storage capacity is described by the Langmuir sorption isotherm and is related to the adsorbed gas content and pressure [11]. Large volumes of CBM are deposited in the internal surface area of the coal's micropores and in the larger pores of its surface, while small amounts of methane can be found in the void spaces as coal shrinks after deposition.

Methane occurs in coal deposits at pressures higher than in atmospheric conditions, and thus, methane desorption is limited because of the nonlinear Langmuir-type isotherm. Macropores (cleats) of the coal matrix are the main track for the flow of gas [12]; however, pressure needs to decrease significantly below the critical desorption pressure in order to promote desorption, as in the case of the mining process. The system of cleats is divided into face cleats that are continuous and provide connectivity and butt cleats that are noncontinuous and often end at face cleats. The production of CBM from the surface of coal involves the dewatering of cleats, which leads to a pressure decrease in the reservoir, liberating the methane adsorbed on the coal face so that it flows through the macropore fracture system to the wellbore [13].

Geological characteristics, such as the thickness and tightness of the overburden and deposit tectonics, are crucial for the desorption of CBM deposits [14]. In addition, pore characteristics as well as the heterogeneity, coal rank, metamorphic degree of coal reservoirs, as well as the composition of CBM gases are key factors affecting the migration and extraction of CBM [15,16]. It has been previously reported that during low-temperature and low-pressure $N_2$ adsorption experiments, the adsorption of $N_2$ molecules on lignite was higher than those found on bituminous coal and anthracite [17,18]. Lignite deposits are generally located near the surface of the earth and are characterized as lightly metamorphosed natural carbonaceous materials with a higher porosity as compared with subbituminous coal [19]. Broader studies focusing on the processes of sorption and release of CBM from lignite deposits would play an important role in evaluating the potential LCBM (lignite coalbed methane) production from fossil coal–natural gas systems, relying heavily on laboratory core analysis (using crushed coal samples) and reservoir characterization, in view of a future methane exploitation. However, there are very few methane sorption/desorption studies on coal samples derived from lignite reservoirs so far [14,20–24].

Lignite is one of Greece's most valuable mineral resources used for electric power production. Greek lignite reserves are in terrestrial or xylitic deposits and occur mainly in the western part of the country (Region of Western Macedonia, Greece). According to the Public Power Corporation (PPC), the original resources have been estimated at 5 billion tons. The Region of Western Macedonia and, in particular, the areas of Ptolemaida, Amynteo, and Florina have the largest lignite capacity in Greece, with total deposits of 1.9 billion tons [25]. In the Ptolemaida basin, a total of eight lignite deposits have been recorded, with three lignite mines (south field mine, Ypsilanti or southwest mine, and Mavropigi mine; Figure 1) near the Ptolemaida power station (Figure 2), which is a 1210-megawatt coal-fired power station with five units [26]. Considering that the Greek plan to stop burning lignite to produce energy according to the "Just Transition Development Plan 2021-27" of Western Macedonia, this has not yet been seen [27,28]; the recovery of an exploitable energy source from its lignite deposits will accelerate the forthcoming exit from the era of coal use. Thus, the beneficial exploitation of lignite deposits could reduce the climate change impact through the mitigation of GHG sources [29]. However, the unconventional hydrocarbon potential resources, i.e., LCBM, of the country are not well known, since detailed investigations are lacking.

Based on the above, the aim of the present study was to evaluate the presence of methane in the lignite deposits of the Ptolemaida basin. For this purpose, three lignite subsoil samples were collected from different sites of the southern field mine, reflecting the average petrographic composition of the lignite coal. Desorption experiments were conducted using the gas channeling process at four different temperatures, in order to evaluate the LCBM that could be extracted from the deposits of the area. Taking into account the results from the desorption process, a SWOT analysis was performed focusing on the strengths, weaknesses, opportunities, and threats of potential LCBM exploitation in Greece as a supplement to natural gas for enhancing energy security.

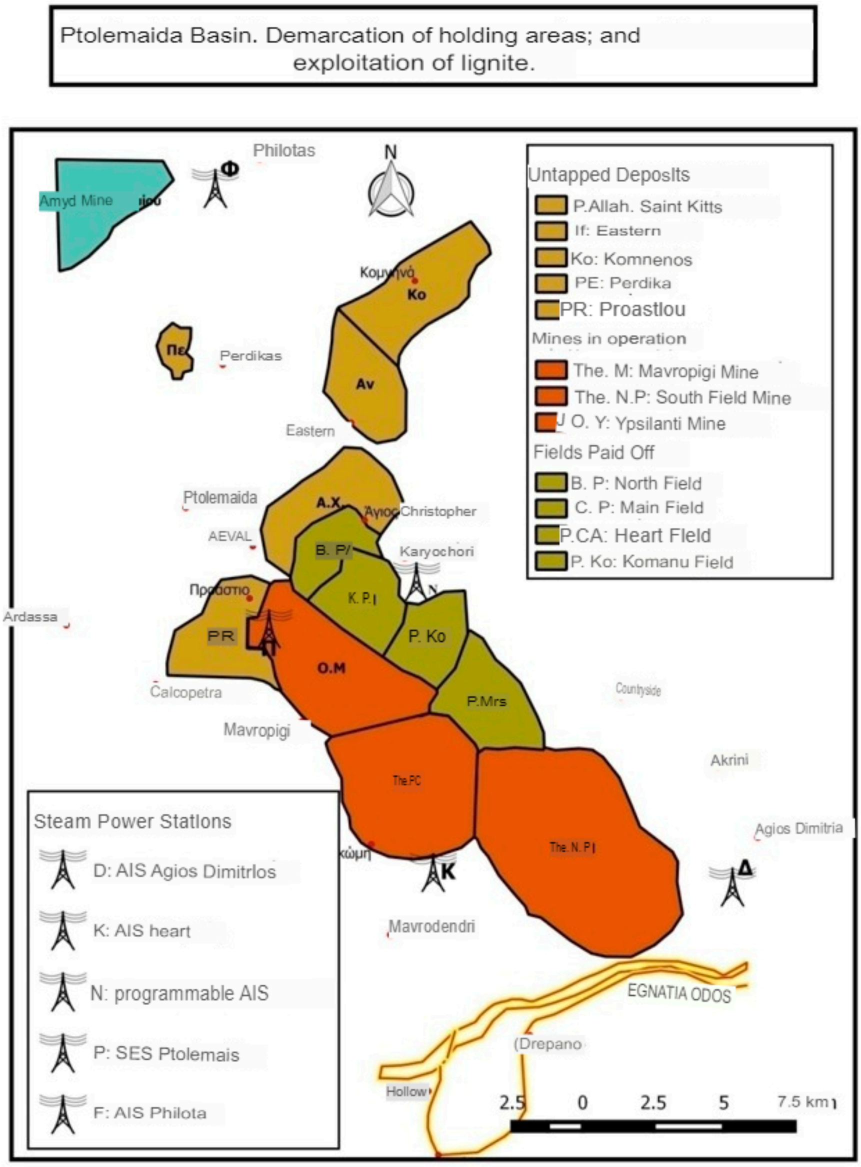


**Figure 1.** Map of Ptolemaida's active mines and lignite deposits.

**Figure 2.** Ptolemaida's power station from PPC archives.

## 2. Geological Structure of Ptolemaida's Lignite Deposits

The Ptolemaida's lignite deposits are located near the Ptolemaida power station [26] in the region of Western Macedonia, Greece. The geological bedrock of the area consists almost entirely of sediments from the Mesozoic cover and the Pelagonian zone [30]. The lignite deposits of the Ptolemaida basin belong to the middle series of Pliocene lignites, with alternations of thin lignite layers with clays and marls. The lignite's color is brown and/or black (Figure 3), and it is deposited in topogenic peatlands with low vegetation.

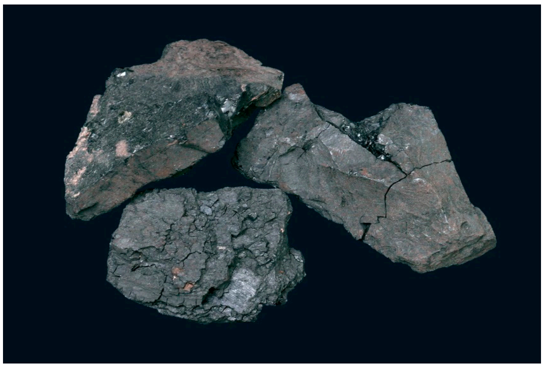

**Figure 3.** Sample of lignite deposits from Ptolemaida basin.

The lignite deposit of the southern field mine, located in the central part of the Ptolemaida basin, is classified as an earthy soft lignite of the pliocene series. The series expands over the central area of the basin and is the thickest (over 300 m) in the basin. The lignite-bearing layer in the southern part is large due to the existence of cosedimentary transitions that separate the southern field from that of the Kardia (heart) completed field. The xylitic layers of the upper layer of the southern field have been deposited in a stagnant environment of a topogenic bog woodland, with mixed vegetation of coniferous and herbaceous plants in a humid and warm climate [31]. According to a petrographic composition analysis, the lignite deposit is mainly composed ofy huminite macerals (69.0–91.9%), with humotelinite present in high concentrations (40.1–48.6%) [30].

## 3. Experimental Section

### 3.1. Sample Collection and Preparation

For the methane desorption evaluation experiments, 3 lignite samples were taken from the subsoil of the southern field mine located at Ptolemaida basin. The sample collection sites, called South Submerged, South T5, and South 53, were chosen in order to reflect the average petrographic composition of the coal deposit. Lignite samples (1 kg each) were collected during the drilling of the holes at a depth of 220 m. The sampling procedure was conducted avoiding the disturbance of the samples' structures and soil tissue, according to the following standards:

- Thin-walled samplers were used to minimize friction between the sampler and soil;
- The equipment had been properly maintained before the sampling;
- The bottom of the borehole had been cleaned through a continuous circulation of fluid;
- The movement of the sampler was slow to avoid impact;
- The sampler advance was shorter than the length to avoid compressing the sample.

The total moisture content by weight of the lignite samples was analyzed in accordance with the International Organization for Standardization ISO 5069-2 [32]. The ash content was measured using the procedure reported in ISO 13909-7 [33]. The net calorific value of the samples was determined according to ISO 1928:2009 [34]. The reduction of particle size procedure was performed in accordance with the international standard ISO 13909-4 [35] resulting in crushed coal samples (Figure 4).

**Figure 4.** Crushed coal samples.

### *3.2. Desorption Experiments*

The desorption process from the porous lignite material follows the general principle of applying gas flow (high purity argon Ar) in order to entrain the gases that are adsorbed on the surface and the interior of the lignite, i.e., $CO_2$, CO, $CH_4$, etc. The release of these gases from the surface and the interior of the porous lignite material is achieved by the pressure of the gas flow overcoming the forces that hold the gases in the lignite pores (van der Waals forces).

Desorption tests were conducted under low and high temperatures to investigate the methane desorption from lignite in order to evaluate temperature effects on gas desorption [36,37]. The desorption process of the three lignite samples from the southern field of the Ptolemaida basin was evaluated at four different temperatures: 25 °C, 50 °C, 100 °C, and 150 °C at standard atmospheric pressure (1 atm). The pressure of the desorption process is equal to the atmospheric pressure because, at these temperatures, any increase in pressure could cause the ignition of the methane produced. The desorption tests were performed using a fixed-bed quartz reactor with an internal diameter of 0.9 cm and a total height of 40 cm, under ambient pressure. A schematic representation of the equipment used is given in Figure 5. For the desorption experiments, 3.0 g (dry weight) of each lignite sample was used to fill the reactor up to a height of 7.1 cm. The bed of the packaging material (called desorbent bed) was supported on both sides of the reactor by inert quartz. The bed geometry (height/diameter) was 7.88. The temperature of the reactor was measured by a type K thermocouple located in its center. The temperature of the reactor furnace could reach a wide range of operating temperatures (up to 800 °C) and was monitored by a type K thermocouple.

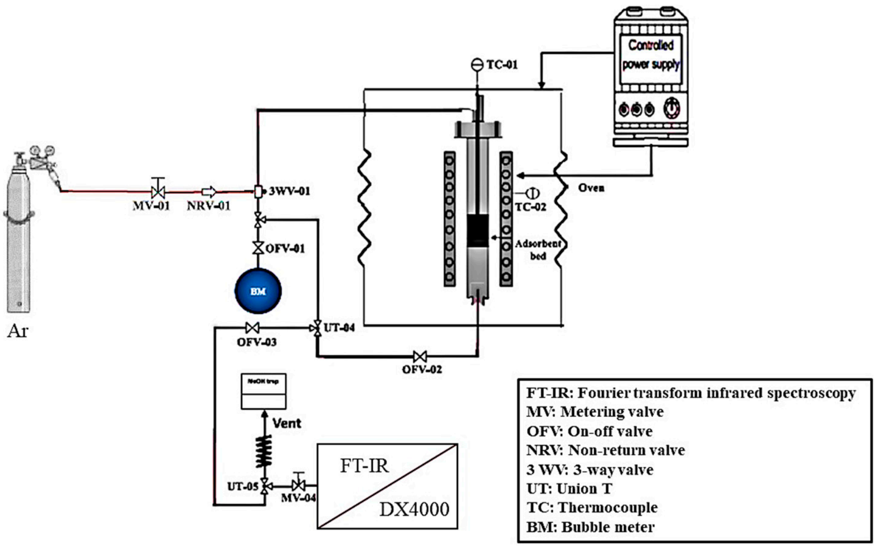


**Figure 5.** Schematic representation of the experimental equipment used for the desorption experiments.

Desorption experiments at 25 °C, 50 °C, 100 °C, and 150 °C were performed using a gas flow at 200 mL/min of high purity Ar (5.0). All samples were subjected to an 8 min degassing process, channeling 1.6 L of Ar gas. The gas flow was controlled through a stainless-steel dosing valve provided by PARKER. Airflow was carefully measured using a bubbler gauge prior to the start of each experiment. The compositions of the reactants and gas flow products were continuously monitored using an analytic system that included an analyzer (FTIR) (Gasmet DX 4000) for the analysis of $H_2O$, CO, $CO_2$, $CH_4$, $C_3H_6$, and $C_3H_8$.

## 4. Results and Discussion

### 4.1. Sample Characterization

The total moisture content by weight of the lignite samples was 55.5% for sample South 53, 55.7% for sample South T5, and 46.7% for sample South Submerged. The ash content after combustion of the lignite was similar for all samples (ca. 23% by weight) (Table 2). The net calorific value of the samples was in the range from 1350 to 1352 (kcal/kg).

**Table 2.** Results of chemical analysis of three southern field lignite samples (% by weight).

| Sample | South 53 | South T5 | South Submerged |
|---|---|---|---|
| Total moisture (% by weight) | 55.5 | 55.7 | 46.7 |
| Dry ash (% by weight) | 23.2 | 23.5 | 23 |
| Net Calorific Value (Kcal/kg) | 1350 | 1352 | 1351 |

### 4.2. Methane Desorption

Coal is a medium with a high specific surface area and serves as the primary storage site for gas adsorption. The more developed the pores, the greater the gas adsorption capacity. The adsorption and desorption gas in coal are in a dynamic equilibrium stage under specified circumstances, and the equilibrium state will be disrupted if any condition changes, such as the temperature [38]. A greater temperature enhances methane desorption and diffusion since the thermal motion of methane molecules is enhanced with temperature and as a result, energy is supplied for methane desorption, making the adsorption effect between the methane molecules and molecules at the coal surface weaker [39].

Based on the above, the collected lignite samples were exposed to Ar gas using four different temperatures, and the synthesis of the produced gas stream was analyzed in order to quantitatively evaluate the amount of $CH_4$ that could be extracted. Figure 6 shows the results from the methane desorption process at 25 °C, 50 °C, 100 °C, and 150 °C for the three tested samples. It was observed that the highest amount of $CH_4$ (in ppm of the produced gas stream) that was extracted from a 3 g sample was reached at desorption conditions of 50 °C and 1 atm. Adsorption between the CBM and lignite is a physical process; thus, the CBM needs to absorb energy to break away from the surface and to overcome the intermolecular gravitational force between molecules [38]. Therefore, more energy is given as the temperature rises from 25 to 50 °C.

However, further temperature increases (from 50 to 100 °C and up to 150 °C) had negative effects on the amount of $CH_4$ produced. A high temperature negative effect on desorption has been previously reported in other research studies on coal samples, which have shown that $CH_4$ production from coal decreases with the increase in temperature under the same conditions of pressure. This could be attributed to changes in lignite layer permeability, due to the possible lignite matrix shrinkage occurring with temperature reductions, leading to increased gas desorption [40]. As it was mentioned in the Section 1, the lignite samples used are mainly composed of huminite macerals (69.0–91.9%). It is also noteworthy that in such elastic adsorptive solids, like lignite coal, the desorption process could be affected by factors such as the specific surface area, pore size distribution, moisture content, coal type (rank, maceral composition, ash, and mineral matter content), etc. [41]. Moreover, swelling and shrinking, which change the original volume of the coal developing linear and volumetric strains, may affect the desorption process. Sun et al. [42] reported that hysteresis of methane desorption first decreases and then increases with an increase in temperature, due to the decrease of moisture and volatile content which makes the pores more unblocked. The thermal expansion of the coal caused by heat treatment leads to a change in the pore structure (increase in pores and the narrowing of the pore throat) and diffusivity. Therefore, further investigation is needed to reveal the exact mechanism responsible for low desorption at elevated temperatures.

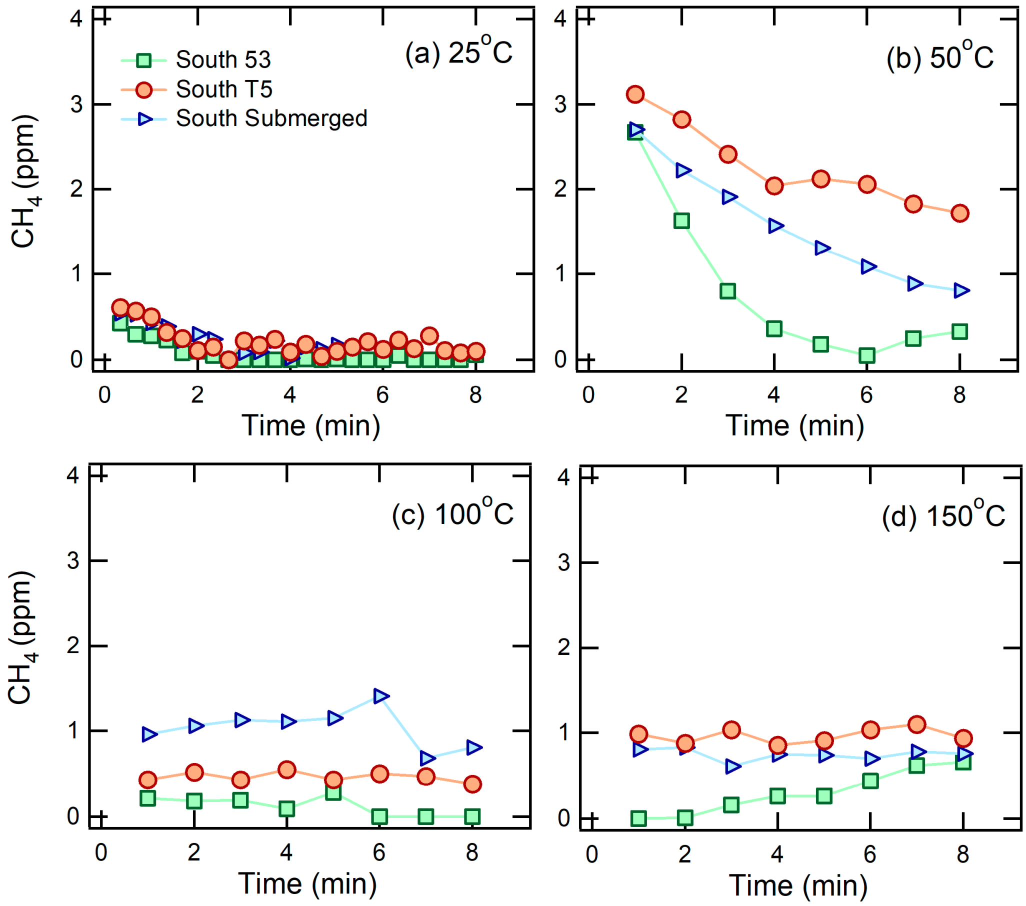


**Figure 6.** Methane quantity in ppm desorbed from 3 g sample during desorption experiments at (**a**) 25 °C, (**b**) 50 °C, (**c**) 100 °C, and (**d**) 150 °C.

The total amount of $CH_4$ desorbed during the whole desorption process at 50 °C was 6 ppm/g of lignite from the South T5, 4.2 ppm/g of lignite from the South Submerged, and 2.1 ppm/g of lignite from the South 53 (Figure 6b). The total amount of methane extracted at 50 °C from all three samples of the southern field in the Ptolemaida basin, considering the amount of $CH_4$ found in the 1.6 L of Ar gas channeled during the degassing process, was found to be 0.82 $m^3$/kg. Taking into account the total lignite deposits (1.9 billion tons deposits) in the Region of Western Macedonia, Greece, the exploitable LCBM could reach comparable levels to those that have been reported for the region of Europe ($7.7 \times 10^{12}$ $m^3$ $CH_4$, [3]), showing a high potential for the sustainable exploitation of Greece's LCBM reservoirs. Considering that 1 $m^3$ of $CH_4$ can produce 4 $kWh_{el}$ [43], the amount of methane stored in the area corresponds to a significant percentage of needs of the electric power production estimated for Greece [25].

Figure 7 shows the composition analysis of the produced gas at desorption conditions of 50 °C for the three tested samples. It was observed that the $CO_2$ content by volume dominates in a higher extent to the gas content of the South 53 (84%) and of the South Submerged (47%) samples, as compared to the gas content of the South T5 sample (24%). The South T5 sample was proved to have a higher $CH_4$ content by volume (2%) as compared to the South

53 and the South Submerged samples. Moreover, the volume percentage of heavier hydrocarbons (propane and propene) of the South T5 sample was about 38%, which is higher than the 7.5% and the 26% in the South Submerged and South 53 samples, respectively.

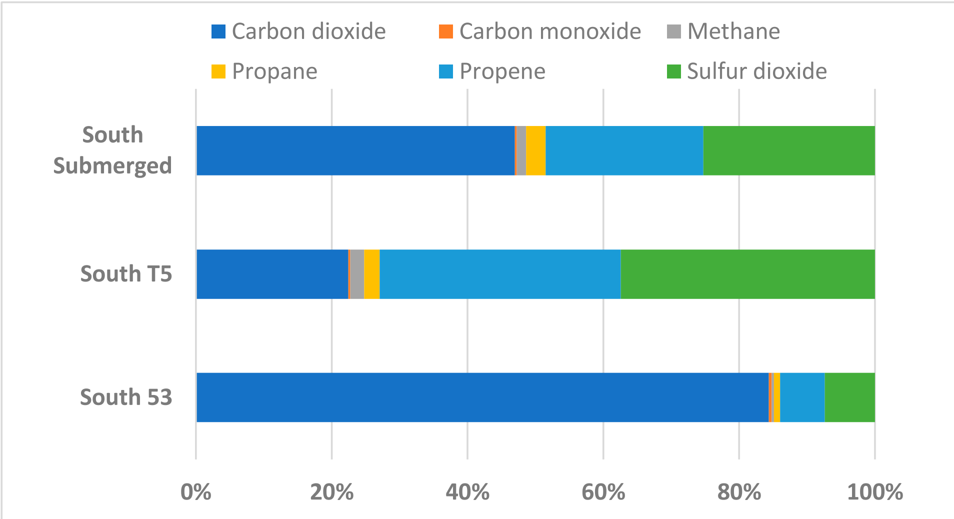


**Figure 7.** Percentage of the gases detected in each LCBM sample.

The knowledge of the exact gas composition of the gas inside deposits could empower the LCBM market to become technologically developed to preferentially extract the gases from deposits that have a higher content of heavier hydrocarbons (such as propane and propene), due to their higher calorific value than $CH_4$ and their higher market value [44]. On the other hand, the $CO_2$ that could be extracted in high quantities reduces the gas's market price and requires the use of expensive removal technologies such as water scrubbing, amino and alkaline solutions, membrane separation, cryogenic separation, or conversion to high added-value products [45]. Therefore, the LCBM extraction operation could be properly designed considering the economic benefits and the environmental impact of the process, based on the information about the identified components ($CO_2$, $CH_4$, and heavier hydrocarbons) of the adsorbed gas from the lignite deposits.

### 4.3. SWOT (Strengths, Weaknesses, Opportunities, and Threats) Analysis

Considering the challenges and prospects of the Greek LCBM deposits, a SWOT analysis was conducted to assess the contribution of LCBM exploitation towards Greek energy security, considering the social, economic, and environmental impact in the nexus of sustainable development. Therefore, the strengths, weaknesses, opportunities, and threats related to LCBM exploitation in Greece were identified in the frame of innovative economy and sustainability (Table 3) [46].

With regard to the strengths of LCBM exploitation in Greece, it should be stated that the lignite in mined deposits in the Region of Western Macedonia amounts to 1.9 billion tons, which proves that the utilization of the methane derived from them is a clear advantage of the region. Specifically, in the Ptolemaida basin, there are eight lignite deposits and three of them are currently being exploited, showing the great potential in this area. Methane, which is a gas of high energy, constitutes a serious threat during mining activities; therefore, its safe extraction from lignite deposits lowers the level of risk of explosion or fire in active coal mines. In addition, methane extraction in active coal mines, which will be carried out on the basis of energy and environmental regulations as well as health and safety regulations, could prevent its flow out, as a potent greenhouse gas, to the atmosphere during mining operations. This course of action is expected to reduce the negative impact of mining on the environment and improve economic efficiency from the extraction and industrial use of methane. In addition, LCBM is a cleaner fuel, with a significantly lower carbon footprint as compared with the coal-based power industry.

**Table 3.** SWOT analysis regarding the LCBM technology development in Greece.

| | |
|---|---|
| **STRENGTHS**<br>• LCBM extraction lowers the level of risk of explosion in active coal mines<br>• LCBM is a cleaner fuel with a lower carbon footprint as compared to the coal-based power industry<br>• Ensures Greece's smoother transition to the coal exit era<br>• Secures energy autonomy of the country<br>• Smaller quantities of fuel from abroad are needed<br>• Protect social welfare | **WEAKNESSES**<br>• LCBM deposits have not been identified yet<br>• LCBM technology is an underdeveloped field<br>• There is no technological training on the LCBM extraction process<br>• High operating cost<br>• Development of transport infrastructure |
| **OPPORTUNITIES**<br>• Minimization of the negative environmental impact of mining activities<br>• Innovative technological solutions in collaboration with the University of Western Macedonia, Greece<br>• Sustainable development of the social, scientific, and economic sectors | **THREATS**<br>• Improper LCBM extraction could release great amounts of $CH_4$ and $CO_2$ into the atmosphere<br>• Large surface footprint and land disturbance |

The exploitation of LCBM ensures Greece's smoother transition to the forthcoming coal exit era, securing the energy autonomy of the country. Moreover, it helps preserve the already existing jobs that will disappear after lignite leaves the energy scene, especially in the Region of Western Macedonia (Greece), which suffers from high unemployment rates. In times when the renewable energy sources will not be able to meet the country's energy requirements, methane gas could act as a valuable supplementary energy source.

Based on the above, the development of the LCBM market from lignite has many strengths, which should contribute to the country's energy autonomy. It is clear that the production of domestic fuels ensures the energy security of a country; for example, in times of war or turmoil the normal supply of natural gas from other countries is threatened and, in such cases, LCBM becomes a lifesaver. When a region produces its own fuel, the economic benefits it reaps are very large. The region can secure existing jobs, purchases smaller quantities of fuel from abroad, and protect social welfare as a result of that economic prosperity.

The Idea of using LCBM gas in Greece was initially generated in order to improve safety during mining activities. However, the main weaknesses are that LCBM deposits in Greece have not been identified yet, LCBM technology is still an underdeveloped field in Greece, and there is no technological training on LCBM extraction process. Therefore, the inefficient organizational structures of mines and coal companies makes decision-making long and complicated, and in many cases, incomprehensible. This results in poor production flexibility and difficulties in adaptation to market demands. Another weakness of Greek coal mines is their low efficiency and productivity related to the limited use of their technical potential (i.e., equipment and machinery). Moreover, the locations of good coal deliverability or those with optimal gas content have not been identified yet, and the mapping deliverability should be the primary objective of a future analysis. These are significant disadvantages for the development of the LCBM exploitation industry in Greece. In addition, the complex geological characteristics may differ radically from those of other countries, posing many technological restrictions on the development of LCBM. Therefore, due to the complexity and lack ofIIce in unconventional resources compared to conventional ones, there are many challenges that require the use of appropriate knowledge in order to start the production. Moreover, LCBM exploration and development was slowed down due to fluctuations in global energy markets, limited policies, and other challenges related to the higher operating costs and low return on investments. Another issue to be considered is the development of transport infrastructure and hydraulic fracturing operations.

The LCBM market development can offer many opportunities to the Western Macedonia region and generally to the whole country. Currently, the coal mining process of the region is characterized by a negative environmental impact, due to the emissions of greenhouse gases ($CH_4$ and $CO_2$) into the atmosphere and the generation of large amounts of waste, water pollution, etc. [47].

The well designed and controlled LCBM exploitation from lignite's deposits offers a great opportunity to minimize the environmental impact of mining activities. In addition, innovative technological solutions in collaboration with the scientific community of the School of Engineering at Western Macedonia University (UOWM, Greece) towards safe LCBM extraction as well as methanation of $CO_2$ present in the extracted gas will contribute to the sustainable development of the social, scientific, and economic sectors of the country. As a matter of fact, scientific and research facilities at UOWM and other universities, working in close cooperation with mines, could result in a well-educated workforce and the improvement of employee competence. The development of a university program including several projects improving technical innovation, organization, and many other solutions for safety and implementation in practice could ensure a continuous supply of qualified personnel and workers to the LCBM industry.

The threats are correlated with the challenges that the LCBM industry faces. An improper LCBM extraction can release great amounts of methane and $CO_2$ into the atmosphere, causing various environmental problems, such as global warming and tropospheric ozone formation. Environmental issues associated with the extraction of LCBM may vary during different stages of the production. They can start from the exploration of the field and development of facilities and continue through to the production operations. Regarding the exploration phase, the rational management of the aquifer during the drilling of the boreholes is quite difficult. Another environmental challenge that the LCBM industry faces is the large surface footprint created by the well thickness and surface infrastructure. To achieve maximum recovery, unlike conventional oil and natural gas production, LCBM production requires the drilling and development of several wells with a short distance between them. However, this causes a major land disturbance which in turn leads to soil desertification and further contamination of the aquifer. At the same time, there are economic assessment concerns. Similar to conventional resources, the development of unconventional resources, including LCBM, requires economic evaluation. In fact, they require more thought from an economic point of view as opposed to conventional resources because of the cost factor (Table 3).

## 5. Conclusions

The Region of Western Macedonia, Greece, a well-known lignite coal basin, was for many years the main energy supplier, covering most of the Greek energy demands. The results presented herein showed that this Greek region could support the energy demands of the country even after the forthcoming coal-exit era, by using methane from its lignite deposits. The amounts of LCBM extracted from the selected samples collected from a representative site of the region (Ptolemaida basin) was significantly high, with an average value of 0.82 $m^3/kg$. The total LCBM that could be extracted from the Western Macedonia region deposits may possibly ensure energy security, by producing up to 80% of the electric power of the country. However, gas composition should always be taken into account for economical LCBM exploitation with the direct beneficial impact on society being aligned with environmental sustainability. All these considerations discussed using a SWOT analysis showed that the strengths and opportunities raised from a potential LCBM exploitation in Greece, and especially in Western Macedonia region, are of great importance for contributing towards energy security in the nexus with social and environmental sustainability.

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## References

1. BP Statistical Review of World Energy. Statistical Review of World Energy 2022. 2022. Available online: https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2022-full-report.pdf (accessed on 12 December 2023).
2. ExxonMobil. *Outlook-for-Energy-Exxon*; ExxonMobil: Houston, TX, USA, 2018.
3. Muther, T.; Qureshi, H.A.; Syed, F.I.; Aziz, H.; Siyal, A.; Dahaghi, A.K.; Negahban, S. Unconventional hydrocarbon resources: Geological statistics, petrophysical characterization, and field development strategies. *J. Pet. Explor. Prod. Technol.* **2022**, *12*, 1463–1488. [CrossRef]
4. CBM Market Analysis. *Coal Bed Methane Market*; Grand View Research, Inc.: San Francisco, CA, USA, 2022.
5. European Commission. *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: A Policy Framework for Climate and Energy in the Period from 2020 to 2030*; European Commission: Brussels, Belgium, 2014.
6. Al-Jubori, A.; Johnston, S.; Boyer, C.; Lambert, S.W.; Bustos, O.A.; Pashin, J.C.; Wray, A.; Lewis, R.; City, O.; Oklahoma, U.; et al. Coalbed Methane: Clean Energy for the World. *Oilfield Rev.* **2009**, *21*, 4–13.
7. Cai, J.; Xu, C.G.; Xia, Z.M.; Chen, Z.Y.; Li, X. Hydrate-based methane separation from coal mine methane gas mixture by bubbling using the scale-up equipment. *Appl. Energy* **2017**, *204*, 1526–1534. [CrossRef]
8. Mokhatab, S.; Poe, W.A.; Mak, J.Y. Natural gas fundamentals. In *Handbook of Natural Gas Transmission and Processing Principles and Practices*; Saad, J., Ed.; Gulf Professional Publishing: Houston, TX, USA, 2018; pp. 1–35.
9. Jian, K.; Fu, X.; Chen, Z.; Li, M.; Xu, X.; Guo, Y.; Liu, J.; Liu, M. Organic geochemical characteristics of coal biogasification. *Fuel* **2022**, *330*, 125637. [CrossRef]
10. Mayumi, D.; Mochimaru, H.; Tamaki, H.; Yamamoto, K.; Yoshioka, H.; Suzuki, Y.; Kamagata, Y.; Sakata, S. Methane production from coal by a single methanogen. *Science* **2016**, *354*, 222–225. [CrossRef] [PubMed]
11. Olajossy, A.; Cieślik, J. Why coal bed methane (CBM) production in some basins is difficult. *Energies* **2019**, *12*, 2918. [CrossRef]
12. Clarkson, C.R.; Pan, Z.; Palmer, I.; Harpalani, S. Predicting Sorption-Induced Strain and Permeability Increase with Depletion for Coalbed-Methane Reservoirs. *Soc. Petrol. Eng.* **2010**, *15*, 152–159. [CrossRef]
13. Seidle, J. *Fundamentals of Coalbed Methane Reservoir Engineering*; PennWell Corp.: Tulsa, OK, USA, 2011.
14. Macuda, J.; Nodzeński, A.; Wagner, M.; Zawisza, L. Sorption of methane on lignite from Polish deposits. *Int. J. Coal Geol.* **2011**, *87*, 41–48. [CrossRef]
15. Jiang, P.; Xu, H.; Wu, H.; Xin, F.; Zhao, T.; Chen, X. Pore characteristics and its heterogeneity of lignite reservoir in the Erlian Basin of Inner Mongolia, China. *Energy Explor. Exploit.* **2022**, *40*, 1555–1572. [CrossRef]
16. Zhong, D.L.; Daraboina, N.; Englezos, P. Coal mine methane gas recovery by hydrate formation in a fixed bed of silica sand particles. *Energy Fuels* **2013**, *27*, 4581–4588. [CrossRef]
17. Hong, L.; Wang, W.; Gao, D.; Liu, W. Critical pore size for micropore filling in coal samples with different rank coals. *PLoS ONE* **2022**, *17*, 264225. [CrossRef] [PubMed]

18. Wang, W.; Hong, L.; Gao, D.; Lun, J. Filling characteristics of the micropores in coals with different metamorphic degrees. *AIP Adv.* **2021**, *11*, 125016. [CrossRef]
19. Baran, P.; Jodlowski, G.S.; Zarebska, K. Sorption of $CO_2$ in lignites from Polish coal mines: Measurements and thermodynamic analysis. *Adsorption* **2016**, *22*, 839–846. [CrossRef]
20. Szafranek-Nakonieczna, A.; Zheng, Y.; Słowakiewicz, M.; Pytlak, A.; Polakowski, C.; Kubaczyński, A.; Bieganowski, A.; Banach, A.; Wolińska, A.; Stępniewska, Z. Methanogenic potential of lignites in Poland. *Int. J. Coal Geol.* **2018**, *196*, 201–210. [CrossRef]
21. Wang, B.; Qin, Y.; Shen, J.; Zhang, Q.; Wang, G. Pore structure characteristics of low- and medium-rank coals and their differential adsorption and desorption effects. *J. Pet. Sci. Eng.* **2018**, *165*, 1–12. [CrossRef]
22. Zhou, S.; Liu, D.; Cai, Y.; Yao, Y. Gas sorption and flow capabilities of lignite, subbituminous and high-volatile bituminous coals in the Southern Junggar Basin, NW China. *J. Nat. Gas. Sci. Eng.* **2016**, *34*, 6–21. [CrossRef]
23. Saralov, A.I. Methane sorption on brown and sapropelite coals. *Solid. Fuel Chem.* **2010**, *44*, 310–314. [CrossRef]
24. Macuda, J.; Baran, P.; Wagner, M. Evaluation of the Presence of Methane in Złoczew Lignite: Comparison with Other Lignite Deposits in Poland. *Nat. Resour. Res.* **2020**, *29*, 3841–3856. [CrossRef]
25. Kaldellis, J.K.; Zafirakis, D.; Kondili, E. Contribution of lignite in the Greek electricity generation: Review and future prospects. *Fuel* **2009**, *88*, 475–489. [CrossRef]
26. Ptolemaïda Power Station. [WWW Document]. 2023. Available online: https://www.gem.wiki/Ptolema%C3%AFda_power_station (accessed on 12 December 2023).
27. Beyond Coal Europe. *Greece Brings Coal Exit Forward Three Years to 2025 [WWW Document]. The Green Tank*; Beyond Coal Europe: Berlin, Germany, 2021.
28. Pavloudakis, F.; Roumpos, C.; Karlopoulos, E.; Koukouzas, N. Sustainable rehabilitation of surface coal mining areas: The case of greek lignite mines. *Energies* **2020**, *13*, 3995. [CrossRef]
29. Evagelopoulos, V.; Begou, P.; Zoras, S. In-Depth Study of PM2.5 and PM10 Concentrations over a 12-Year Period and Their Elemental Composition in the Lignite Center of Western Macedonia, Greece. *Atmosphere* **2022**, *13*, 1900. [CrossRef]
30. Antoniadis, P.; Mavridou, E.; Gentzis, T. The Notio Pedio (Southern Field) lignite deposit in the Ptolemaida Basin, Greece: Depositional conditions as revealed through petrography. *Energy Sources* **2005**, *27*, 1117–1131. [CrossRef]
31. Metaxas, A.; Karageorgiou, D.E.; Varvarousis, G.; Kotis, T.; Ploumidis, M.; Papanikolaou, G. Geological evolution-stratigraphy of Florina, Ptolemaida, Kozani and Saradaporo graben. *Earth-Sci. Rev.* **2018**, *179*, 392–410. [CrossRef]
32. *ISO 5069-2*; Brown Coals and Lignites—Principles of Sampling—Part 2: Sample Preparation for Determination of Moisture Content and for General Analysis. ISO: Geneva, Switzerland, 1983.
33. *ISO 13909-7*; Hard Coal and Coke—Mechanical Sampling—Part 7: Methods for Determining the Precision of Sampling, Sample Preparation and Testing. ISO: Geneva, Switzerland, 2016.
34. *ISO 1928:2009*; Solid Mineral Fuels—Determination of Gross Calorific Value by the Bomb Calorimetric Method and Calculation of Net Calorific Value. ISO: Geneva, Switzerland, 2009.
35. *ISO 13909-4*; Hard Coal and Coke—Mechanical Sampling—Part 4: Coal—Preparation of Test Samples. ISO: Geneva, Switzerland, 2016.
36. Wang, Z.; Zhu, Z. Experimental Study on the Effects of Different Heating Rates on Coalbed Methane Desorption and an Analysis of Desorption Kinetics. *ACS Omega* **2021**, *6*, 34889–34903. [CrossRef] [PubMed]
37. Wang, Z.; Wang, X. Promotion effects of microwave heating on coalbed methane desorption compared with conductive heating. *Sci. Rep.* **2021**, *11*, 9618. [CrossRef] [PubMed]
38. Ye, Q.; Li, C.; Yang, T.; Wang, Y.; Li, Z.; Yin, Y. Relationship between desorption amount and temperature variation in the process of coal gas desorption. *Fuel* **2023**, *332*, 126146. [CrossRef]
39. Ma, H.; Wang, L.; Jia, H.; Chang, J.; Li, Y.M.; Zhang, X.; Hu, Z.; Yin, Z. Experimental study on desorption characteristics of coalbed methane under variable loading and temperature in deep and high geothermal mine. *Adv. Civil. Eng.* **2020**, *2020*, 8878125. [CrossRef]
40. Fan, Y.; Deng, C.; Zhang, X.; Li, F.; Wang, X.; Qiao, L. Numerical study of $CO_2$-enhanced coalbed methane recovery. *Int. J. Greenh. Gas. Control* **2018**, *76*, 12–23. [CrossRef]
41. Mukherjee, M.; Misra, S. A review of experimental research on Enhanced Coal Bed Methane (ECBM) recovery via $CO_2$ sequestration. *Earth-Sci. Rev.* **2018**, *179*, 392–410. [CrossRef]
42. Sun, L.; Wang, H.; Zhang, C.; Zhang, S.; Liu, N.; He, Z. Evolution of methane ad-/desorption and diffusion in coal under in the presence of oxygen and nitrogen after heat treatment. *J. Nat. Gas. Sci. Eng.* **2021**, *95*, 104196. [CrossRef]
43. Kalogiannis, A.; Vasiliadou, I.A.; Spyridonidis, A.; Diamantis, V.; Stamatelatou, K. Biogas production from chicken manure wastes using an LBR-CSTR two-stage system: Process efficiency, economic feasibility, and carbon dioxide footprint. *J. Chem. Technol. Biotechnol.* **2022**, *97*, 2952–2961. [CrossRef]
44. Ripepi, N.; Louk, K.; Amante, J.; Schlosser, C.; Tang, X.; Gilliland, E. Determining coalbed methane production and composition from individual stacked coal seams in a multi-zone completed gas well. *Energies* **2017**, *10*, 1533. [CrossRef]
45. Vasiliadou, I.A.; Kalogiannis, A.; Spyridonidis, A.; Katsaounis, A.; Stamatelatou, K. Effect of applied potential on the performance of an electroactive methanogenic biocathode used for bioelectrochemical $CO_2$ reduction to $CH_4$. *J. Chem. Technol. Biotechnol.* **2022**, *97*, 643–652. [CrossRef]

46. Brodny, J.; Tutak, M. Challenges of the polish coal mining industry on its way to innovative and sustainable development. *J. Clean. Prod.* **2022**, *375*, 134061. [CrossRef]
47. Brodny, J.; Tutak, M. The Use of the Open Innovation Concept to Develop a Method to Improve Safety during the Mining Production Process: A Case Study of the Integration of University and Industry. *J. Open Innov. Technol. Mark. Complex.* **2022**, *8*, 75. [CrossRef]