



Selection of the Type of Gas Field Development Using Game Theory Methods

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Abstract

This paper applies game theory to the selection of a natural gas field development method in Ukraine. Four states of nature are defined based on the depth of the reservoir and its thickness. For each state, the expected profits from gas production are estimated for three development methods: conventional, shale, and central-basin. The decision-making outcomes are evaluated using the maximax criterion, Wald's maximin criterion, and Savage's minimax regret criterion. The results indicate that the conventional development method yields the highest profitability. To further refine the analysis, the Bayes criterion is applied by incorporating the probabilities of the states of nature. These probabilities are estimated using data from 20 gas fields that have already been explored and are currently in operation. The Bayesian analysis confirms the robustness of the initial findings.

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1. Introduction

Contemporary energy policy in Ukraine and globally is increasingly focused on strengthening energy security through measures aimed at reducing dependence on imported energy resources and diversifying energy supply. These measures include expanding domestic production and the resource base, particularly through the development of unconventional gas resources. Natural gas is one of the key energy sources alongside oil and coal. Despite the fact that natural gas reserves in Ukraine's underground storage facilities amounted to 12.055 billion cubic meters as of September 2025, this level was lower than in the previous year ^[1]. During the gas injection season, Ukraine faced a deficit of 2.95 billion cubic meters, which was covered only through increased imports ^[1]. This indicates structural challenges in domestic gas supply that are mitigated by external support, posing risks to the country's energy and financial independence. These risks are amplified by global trends of rising demand for natural gas, particularly in Asia and Europe, where coal is increasingly being replaced by gas. Compared to coal and oil, natural gas generates lower carbon emissions, making it a relatively cleaner and more attractive energy source. As a result, both demand and prices are expected to increase, further reinforcing the need for domestic resource development. Ukraine possesses significant potential in this area, with three major oil and gas regions across the country and 467 gas fields ^[2]. The strategic importance of domestic gas resources underlies the relevance of this study. However, gas production is associated with high capital costs, significant risks, and uncertainty. Under conditions of economic constraints, such investments must be economically justified, which creates a need to reduce risks and enhance profitability. This, in turn, motivates the application of economic and mathematical methods to determine optimal gas production strategies under uncertainty.

2. Materials and Methods

The methodological framework of the study is based on the application of game theory, specifically games against nature, under conditions of both complete uncertainty and known probabilities of the states of nature. This methodological choice is motivated by the fact that the initial development of any gas field is determined by the selected extraction technology. An incorrect choice of technology may result in irreversible losses that cannot be offset at later stages. The study employs current data on the explored characteristics of the Oleska gas field in Ukraine, as well as data from 20 gas fields worldwide with known parameters regarding reservoir depth and thickness. These data were obtained from publicly available online sources, which are cited in the reference list.

3. Results

3.1. Theoretical Foundations of the Financial Model

The primary objective of financial modeling is to provide a basis for managerial decision-making and to assess the economic feasibility of investments. The financial model developed to justify the choice of a technological strategy for gas field development is based on profit as the objective function of the project. The financial outcome depends on the selected technological strategy and the corresponding state of nature. Within the model, profit is calculated as the difference between total revenue from the sale of the entire volume of explored gas and the total costs of drilling, development, and operation, prior to dividend payments to investors and taxation, i.e. EBITDA.

Project revenue is treated as a stochastic component and depends on the volume of gas produced. The volume of gas is an uncertain variable, as it depends on the state of nature, which cannot be determined *ex ante* with certainty and is known only through geological exploration data. Therefore, revenue is calculated as the product of the market price per cubic meter of gas and the explored gas reserves.

To estimate the unit market price of natural gas per cubic meter, the initial price expressed in euros per megawatt-hour is converted into a comparable form. First, the price per megawatt-hour is divided by the corresponding number of cubic meters, resulting in a market price per cubic meter of gas. Second, the price is converted from euros to US dollars, which is the currency used for financial modeling in this study.

Total development costs consist of three main components. The first component includes the costs of drilling exploratory wells, which represent a mandatory initial stage aimed at reducing geological uncertainty. The second component comprises the costs of drilling production wells, which depend directly on the chosen technological strategy (e.g. vertical or horizontal drilling) and, importantly, on the depth of the reservoir. The third component includes development costs required to bring the wells into commercial operation. This simplified cost structure, which excludes taxes and other payments, is adopted to focus the analysis exclusively on technological uncertainty and the critical dependence of decision-making on geological success. This approach allows for the construction of a payoff matrix that compares the controllable parameter (the technological strategy) with

uncontrollable parameters (reservoir depth and volume) that ultimately determine project profitability.

3.2. Formal problem statement

The formal problem of selecting an investment strategy for the technological development of a natural gas field is framed as the maximization of expected financial outcomes under geological uncertainty. To this end, a payoff matrix is constructed, where each element represents the profit obtained from choosing a specific controllable strategy under a particular uncontrollable state of nature, defined by a combination of reservoir depth and gas volume. Profit is calculated as the difference between revenue and costs, both of which depend on the chosen strategy and the realized state of nature. Each state of nature is associated with an a priori probability, providing a quantitative estimate of the likelihood of each possible geological scenario. The states of nature are mutually exclusive, and each a priori probability is expressed as a value between 0 and 1.

Due to limited direct drilling data for the Oleska field, these probabilities are determined through statistical analysis of analogous fields worldwide. This approach converts qualitative geological risk into a measurable stochastic variable, which is essential for computing the expected profit for each alternative technological strategy. The objective of the model is to select the optimal strategy for which the expected profit, calculated as the sum of the products of profits and their corresponding probabilities, is maximized.

3.3. Formation of the sets of states of nature and strategies

The construction of any economic-mathematical model for decision-making under uncertainty requires prior structuring of all controllable and uncontrollable factors. Strategies represent the possible decisions available to the economic agent, while states of nature characterize external conditions that are beyond the agent's control but determine the performance of each strategy.

Reservoir depth and gas volume were chosen as the key criteria for modeling the states of nature, as they directly influence the technical complexity and economic efficiency of the extraction project. Based on the Production Sharing Agreement^[3], the depth of productive layers at the Oleska field is projected to range from 2,000 to 4,000 meters^[3]. Therefore, the model considers two representative depths: 3,000 meters as the average and 4,000 meters as the maximum, capturing the most pessimistic scenarios for capital expenditure. According to the Geological Service, potential gas reserves at the Oleska field are estimated between 1 and 2 trillion cubic meters^[4]. For the purpose of economic-mathematical modeling, only two reserve levels are considered: 1 trillion and 1.5 trillion cubic meters. This deliberate choice focuses on pessimistic scenarios, ignoring maximum projections (2 trillion cubic meters) to test the investment robustness of the chosen technological strategy under low-reserve conditions.

Combining the two depth levels and the two reserve levels results in four possible states of nature, labeled S1–S4 in Table 1.

Table 1: Characteristics of States of Nature

Designation of states of nature	D, m	V _g , trillion m ³
S1	3000	1
S2	4000	1
S3	3000	1,5
S4	4000	1,5

Where D represents reservoir depth and V_g denotes gas volume.

The Oleska field exhibits a geological structure containing

multiple types of gas reserves, including conventional gas, shale gas, and central-basin gas. Accordingly, the set of strategies, as presented in Table 2, is denoted by A_1 – A_3 .

Table 2: Characteristics of Types of Strategies

Conventional designation of strategy types	Gas type
A1	Traditional
A2	Shale
A3	Central basin

3.4. Construction of the game payoff matrix

To construct the game's payoff matrix, the method of calculating profits for each combination of possible states of nature and extraction strategies was applied. A key element is the determination of the market price of natural gas. Since the Ukrainian market is oriented toward Europe, the price is based on data from the Dutch Title Transfer Facility (TTF) [5]. On the date of the study (17 November 2025) the TTF gas price was €30.46 per megawatt-hour. This price is then converted from euros per megawatt-hour to US dollars per cubic meter.

First, it is noted that 1 megawatt-hour corresponds to 95.31 cubic meters of natural gas [5]. The price per cubic meter in euros is therefore calculated as:

$$\text{Price (€ / m}^3\text{)} = \frac{30.46}{95.31} \approx 0.32 \text{ € / m}^3$$

Then, converting to US dollars at the exchange rate on 17 November 2025 (1 € = 1.14 USD) gives:

$$\text{Price (USD / m}^3\text{)} = 0.32 \times 1.14 \approx 0.36 \text{ USD / m}^3$$

Project costs in this study are considered as the total sum of three main stages: exploratory well drilling, production well drilling, and well development. These cost components are directly influenced by the investment decision and geological uncertainty, making costs a variable dependent on the chosen strategy and the state of nature. Costs therefore serve as the primary metric for comparing the profitability of each strategy.

The number of wells used in calculations is based on the Production Sharing Agreement [3], which assumes 8 vertical and 5 horizontal wells. In the model, these are allocated between functional development stages under the assumption that the 8 vertical wells serve as exploratory wells, as vertical drilling is a basic, less expensive technology necessary for initial confirmation of geological characteristics and reserves. The 5 horizontal wells serve as production wells, as

horizontal drilling is technologically advanced and costly, justified economically only during intensive gas extraction. For conventional gas, all 13 wells are vertical [6]. In contrast, for shale and central-basin strategies, a combination of 8 vertical exploratory wells and 5 horizontal production wells is applied [6].

The model assumes a linear relationship between all costs and depth. The cost of drilling a vertical well to 4,000 meters is \$5 million, equivalent to \$1,250 per meter [7]. The cost of horizontal drilling is \$25 million, or \$6,250 per meter [7].

Well development costs were estimated using graphical data from the "Typical Cost Breakdown for Conventional vs. Unconventional Wells" chart [8], which shows the relative shares of main cost components. Based on visual analysis, the portion of production well drilling cost attributed to development activities was identified. For conventional gas, 43% of drilling cost is allocated to development [8], reflecting minimal development needs. For shale gas, 100% of drilling cost is attributed [8], reflecting mandatory hydraulic fracturing. For central-basin gas, 80% of drilling cost is allocated [8], reflecting the necessity of fracturing but slightly lower than for shale due to better reservoir properties such as permeability.

Based on all parameters above, the profit equation can be formulated as:

$$P = k \times V_g - (m \times D \times n + h \times D \times y + (h \times D \times y) \times b,$$

where P represents profit, k is the price per cubic meter of gas, V_g is the gas volume, m is the cost of exploratory drilling per meter, D is the reservoir depth, n is the number of exploratory wells, h is the cost of production drilling per meter, y is the number of production wells, and b is the percentage of development cost relative to production drilling.

The numerical values of these parameters are presented in Tables 3 and 1. Parameters D and V_g depend on the states of nature rather than on the chosen strategies.

Table 3: Parameter values for each strategy

Designation of strategies	k, USD/m ³	m, USD/m	n, pcs	h, USD/m	y, pcs	b, %
A1	0,36	1250	8	1250	5	43
A2				6250		100
A3						80

Based on the data obtained, a payoff matrix of the game was compiled, which shows the expected results of each strategy.

The amounts in Table 4 are given in US dollars.

Table 4: Profit Matrix, USD

	S1	S2	S3	S4
A1	359943187500	359924250000	539943187500	539924250000
A2	359782500000	359710000000	539782500000	539710000000
A3	359801250000	359735000000	539801250000	539735000000

3.5 Determination of the probabilities of states of nature

Although the optimal strategy can be selected based on the calculated game payoff matrix without considering the probabilities of the states of nature, this approach assumes that all possible states occur with equal likelihood. Such an assumption oversimplifies the situation, as in reality the chances of different scenarios vary. Introducing probabilities is therefore not a requirement of the model but a means to enhance its realism, allowing for the consideration that some geological scenarios are more likely than others. As a result,

decision-making is based not only on possible outcomes but also on the probabilities of their occurrence.

To determine the probabilities of the states of nature, we use empirical data from other gas fields worldwide where reservoir depth and gas volume are known. Since these characteristics are not available for the Oleska field, analyzing such data allows us to estimate the likelihood of different combinations. The results of this analysis are summarized in Table 5.

Table 5: Characteristics of 20 Gas Fields Around the World

Field name	Depth, m	Gas volume, trillion cubic
Marcellus Shale Basin	2438 ^[9]	84 ^[10]
Hainesville Shale Basin	4700 ^[11]	2,1 ^[12]
Eagle Ford Shale Basin	4267 ^[13]	0,6 ^[14]
Montney Basin	3500 ^[15]	12,7 ^[16]
Barnett Shale	2590 ^[17]	1,5 ^[18]
Ufeng-Lunmasi Formations	4500 ^[19]	17 ^[20]
Vaca Muerta Formations	3000 ^[21]	8,7 ^[22]
Lublin Basin	3500 ^[23]	0,35 ^[24]
Utica Shale Basin	2438 ^[25]	1,1 ^[26]
Karoo Basin	2951 ^[27]	14 ^[28]
Powder River Basin	3962 ^[29]	0,0056 ^[30]
Fayetteville Shale Basin	1981 ^[31]	0,9 ^[31]
Troll	1330 ^[32]	1,67 ^[33]
Havar	4270 ^[34]	5,27 ^[34]
Hassi R'Mel	2315 ^[35]	2,4 ^[36]
South Pars	3000 ^[37]	14 ^[38]
Entrem Shale Basin.	762 ^[39]	2,15 ^[40]
Shah Deniz	1000 ^[41]	1,2 ^[42]
Tamar Field	3000 ^[43]	0,28 ^[44]
Detlingen Gas Field	4300 ^[45]	0,0256 ^[46]

Next, the midpoints between the minimum and maximum parameter values adopted in the model were calculated as follows:

$$D_a = \frac{3000+4000}{2} = 3500 \text{ meters}$$

$$V_{ga} = \frac{1+1.5}{2} = 1.25 \text{ trillion cubic meters}$$

where D_a is the average reservoir depth and V_{ga} is the average gas volume.

The number of fields falling into the corresponding depth and volume categories was then determined. Cases where values equal the midpoint were assigned to the first category. This

gives:

- $D_1 (\leq 3500 \text{ m})$ – 14 fields
- $D_2 (> 3500 \text{ m})$ – 6 fields
- $V_{g1} (\leq 1.25 \text{ trillion m}^3)$ – 8 fields
- $V_{g2} (> 1.25 \text{ trillion m}^3)$ – 12 fields

Probabilities of occurrence for each type, denoted as P , are calculated by dividing the number of fields of the corresponding type by the total number of fields (20):

$$P(D_1) = 14/20 = 0.7, P(D_2) = 6/20 = 0.3$$

$$P(V_{g1}) = 8/20 = 0.4, P(V_{g2}) = 12/20 = 0.6$$

where P is the probability, D the depth category, and V_g the volume category.

The probabilities of the states of nature, which are combinations of depth and volume types, can now be computed by multiplying the corresponding probabilities:

$$\begin{aligned} P(S_1) &= 0.7 \times 0.4 = 0.28 \\ P(S_2) &= 0.3 \times 0.4 = 0.12 \\ P(S_3) &= 0.7 \times 0.6 = 0.42 \\ P(S_4) &= 0.3 \times 0.6 = 0.18 \end{aligned}$$

where P represents the probability and S_j denotes the states of nature.

4. Discussion

The solution of the problem is analyzed using game-theoretic methods under conditions of complete uncertainty, where the probabilities of the states of nature are unknown. Specifically, the analysis applies the maximax criterion [47], Wald's maximin criterion [47], and Savage's minimax regret criterion [47]. This approach allows the project to be examined from different perspectives.

The maximax criterion focuses on the optimistic scenario, assuming that all conditions are most favorable for the project. In this case, the decision-maker is willing to take

risks in pursuit of the highest possible profit:

$$\begin{aligned} M &= \max \max V_{ij} = \\ &= \max (539,943,187,500; 539,782,500,000; 539,801, \\ &= 250,000) = 539,943,187,500 \text{ USD} \end{aligned}$$

According to the maximax criterion, strategy A_1 , i.e., conventional gas extraction, yields the highest profit.

Wald's maximin criterion maximizes the minimum profit, reflecting a conservative approach in which the investor anticipates the worst-case scenario:

$$\begin{aligned} W &= \max \min V_{ij} = \\ &= \max (359,924,250,000; 359,710,000,000; 359,735, \\ &= 000,000) = 359,924,250,000 \text{ USD} \end{aligned}$$

Under the maximin criterion, strategy A_1 again provides the highest guaranteed profit.

Savage's minimax regret criterion [47] seeks to minimize the maximum opportunity loss that would occur if an incorrect strategy is chosen. To apply this criterion, a regret matrix is constructed by subtracting each profit from the maximum profit in its column. The resulting regret matrix is presented in Table 6.

Table 6: Risk Matrix, USD

	S1	S2	S3	S4
A1	0	0	0	0
A2	160687500	214250000	160687500	214250000
A3	141937500	189250000	141937500	189250000

Strategy A_1 exhibits the minimum regret, i.e., zero dollars. This indicates that, under any state of nature, no opportunity loss occurs if A_1 is chosen. Therefore, according to the three previously applied criteria—maximax, maximin, and minimax regret—strategy A_1 is identified as the best option.

For the final decision, however, the Bayes criterion [47] is applied, as it incorporates the probabilities of the states of nature. This approach allows consideration of both optimistic and pessimistic scenarios while weighting outcomes by their likelihood. The Bayes criterion is a leading decision-theoretic method used to select an optimal strategy under risk, when the probabilities of various outcomes are known. Its objective in this context is to choose the strategy that maximizes the expected weighted profit across all possible scenarios:

$$E(A_i) = \sum_{j=1}^n V_{ij} \times P_j$$

where $E(A_i)$ is the expected weighted profit, V_{ij} is the profit, and P_j is the probability of state S_j .

Expected weighted profit is a key metric in decision-making under uncertainty because it combines both the magnitude of potential outcomes and their likelihood. Relying solely on the highest or most probable profit can be misleading, as an investment with very high potential returns may have a very low chance of realization, while another with lower returns may be almost guaranteed. Expected profit provides a realistic average return of the project over the long term, reflecting the overall efficiency of each alternative while accounting for all probabilities:

$$\begin{aligned} E(A_1) &= 359,943,187,500 \times 0.28 + 359,924,250,000 \times \\ &= 0.12 + 539,943,187,500 \times 0.42 + 539,924,250,000 \times \\ &= 0.18 = 467,937,506,250 \text{ USD} \end{aligned}$$

$$\begin{aligned} E(A_2) &= 359,782,500,000 \times 0.28 + 359,710,000,000 \times \\ &= 0.12 + 539,782,500,000 \times 0.42 + 539,710,000,000 \times \\ &= 0.18 = 467,760,750,000 \text{ USD} \end{aligned}$$

$$\begin{aligned} E(A_3) &= 359,801,250,000 \times 0.28 + 359,735,000,000 \times \\ &= 0.12 + 539,801,250,000 \times 0.42 + 539,735,000,000 \times \\ &= 0.18 = 467,781,375,000 \text{ USD} \end{aligned}$$

According to the Bayes criterion [47], the optimal strategy is A_1 , i.e., conventional gas extraction, as it provides the highest expected weighted profit of 467,937,506,250 USD.

5. Conclusion

Strategy A_1 , i.e., conventional gas extraction, emerged as the optimal choice, as it provides the highest profits across all possible geological states compared to unconventional strategies A_2 and A_3 . This outcome is explained by the significant differences in development costs. Conventional gas fields typically exhibit higher permeability and porosity, allowing extraction using relatively simple vertical drilling technologies, which keeps costs at a lower level. In contrast, unconventional methods target low-permeability reservoirs, requiring more expensive technologies, with horizontal drilling being a major contributor to the higher costs.

The selection of strategy A_1 is further justified given the unstable economic conditions in the country, which

necessitate increased caution and minimization of financial risks. Since conventional gas development involves lower initial expenditures compared to unconventional methods A_2 and A_3 , it is more resilient to macroeconomic shocks and tax variability. Under conditions of limited or costly capital, choosing the strategy that provides the highest expected profit $E(A_1)$ with lower upfront investment is the most prudent decision. This confirms that, in situations of overall economic uncertainty, it is necessary to select not only the most profitable but also the most capital-efficient strategy, minimizing external risks to the project.

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