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Optimization of the Lateral Length of Shale-Gas Horizontal Wells Based on Geology–Engineering–Economy Integration

Jialin Zhu [1,*], Sha He [1] and Lin Lin [2]

[1] School of Economics and Management, Southwest Petroleum University, Chengdu 610500, China
[2] Southwest Oil & Gas Co. of PetroChina, Chengdu 610051, China
* Correspondence: zhujl@swpu.edu.cn; Tel.: +86-159-8212-9597

Abstract: Horizontal wells with extended lateral lengths and large-scale hydraulic fracturing are a key technology for shale gas development. Lateral length is the key factor in determining the production and economic benefits of horizontal wells. Therefore, based on geology–engineering–economy integration, a method for optimizing the lateral length of shale-gas horizontal wells is established. Through fracture-shape prediction, productivity simulation and input–output analysis, the net present-value model of the technical–economic evaluation of the economic lateral length is established. A comprehensive evaluation of lateral lengths in Changning Block is then conducted. The results show that, under the current geological, engineering, and economic conditions in Changning Block, a horizontal well with a lateral length between 175 m and 3508 m is economically viable, and the optimal economic lateral length is 2000 m. The porosity and thickness of the reservoir matrix, the production time, the drilling investment, and the price of the natural gas wellhead in the first year have a great impact on the economic lateral length. On one hand, we can increase the drilling rate by increasing the technical research and development efforts. On the other hand, we can improve the construction management level to reduce investment and reasonably increase the price subsidy to optimize the lateral length of shale-gas horizontal wells.

Keywords: shale gas; horizontal well; economic lateral length; geology–engineering–economy integration

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Citation: Zhu, J.; He, S.; Lin, L. Optimization of the Lateral Length of Shale-Gas Horizontal Wells Based on Geology–Engineering–Economy Integration. *Processes* **2023**, *11*, 249. https://doi.org/10.3390/pr11010249

Academic Editors: Tianshou Ma and Yuqiang Xu

Received: 19 November 2022
Revised: 7 January 2023
Accepted: 10 January 2023
Published: 12 January 2023

1. Introduction

Energy is the blood of modern society and industrial civilization. China is gradually transforming into a green, low-carbon-energy society, taking steps towards human development as its economy is in a period of steady development. However, at this stage, fossil energy remains the pillar of China's energy consumption, with coal, oil, and natural gas accounting for 85.7% of its primary energy consumption [1]. Natural gas is a relatively clean, low-carbon fossil fuel. It is a practical alternative to low-carbon sources. According to the resource evaluation results, China's shale-gas resource endowment is outstanding, with 21.8×10^{12} m^3 of technically recoverable resources. However, the current proven rate is only 4.79%. The industrial exploitation of shale gas cannot be realized because of its ultra-low porosity, low permeability, and a lack of production capacity depending on the natural energy of the formation. The horizontal well, combined with large-scale hydraulic fracturing technology, has enabled the industrial exploitation of shale gas, which resulted in the shale-gas revolution in the U.S.A. and demonstrated the great value of shale-gas development in China.

After more than ten years of technology tracking, technology transplantation, and independent research and development, China has mastered a series of technologies for shale-gas development using horizontal wells and large-scale hydraulic fracturing. Horizontal wells are a core technology utilized to realize the commercial development of shale gas. The lateral length, which determines the contact area with shale-gas reservoir and the effective length of hydraulic fracturing, is an important technical parameter in determining the productivity of a horizontal well [2,3]. Therefore, it is necessary to determine the economic lateral length of horizontal wells in shale-gas development. Most existing studies focus on the limited technical length of a shale-gas horizontal well from the perspective of drilling or oil production, considering wellbore stability, pump pressure and wellbore friction. Few studies focus on the economic lateral length of shale-gas horizontal wells.

Based on a genetic algorithm, Liu Yusong et al. [4] optimized the lateral length of a horizontal well using the coupling model of the horizontal wellbore and reservoir, taking into account the flow state of fluid in the wellbore, the friction pressure drop, and other factors. Guo Xiaole et al. [5] established the hydraulic extension limit model of extended-reach wells, which showed that the formation safety density window and the maximum allowable total pressure loss were objective constraints on the hydraulic extension limit of extended-reach wells in the Liuhua Oilfield in the South China Sea. Under the existing equipment conditions, the hydraulic extension limit was mainly limited by the pump pressure in the slope-stabilizing section, and the hydraulic extension limit length of the slope-stabilizing section was 6500~7200 m. The horizontal extension length of horizontal wells were determined by different factors and could be divided into three parts, including the acceptable cutting bed height, cutting lifting efficiency, pump pressure, total circulation pressure loss, well bottom pressure, and formation fracture pressure [6]. Based on the established calculation model of the circulating pressure loss of horizontal wells, Xu Kunji et al. [7] studied the lateral extension ability of horizontal wells and found that the hydraulic extension ability of horizontal sections was affected by factors such as drilling fluid density, the rated pressure of drilling pumps, the height of cutting beds, and the drilling-fluid displacement. Jin Xiuju et al. [8] suggested that the lateral length of horizontal wells in the Puguang Gas Field should be maintained within 400–600 m according to the productivity data obtained from a single-well geological model simulation and the analysis of factors such as reservoir thickness and productivity requirements. Yuan Junliang et al. [9] conducted an integrated-rock mechanical study to evaluate the wellbore stability of a shale horizontal well. The results showed that wellbore instability was related to the bedding plane and azimuth angle.

Based on the horizontal-well productivity model, Chen Yaohui et al. [10] built an equation demonstrating the relationship between the cost of the lateral section and the production of a horizontal well to determine the optimal lateral length of a horizontal well in a block in Daqing, combined with economic indicators such as the investment payback period and net present value. Zhou Yingjie [11,12] proposed that the optimal lateral length of oil wells in the area should be 200~250 m, determined via statistical analysis, numerical simulation, analyzing actual data from the Shengli Oil Region, as well as a comprehensive economic evaluation. T. Ariadji et al. [13] established the relationship function between the cumulative gas production and the lateral length to quickly determine the economic lateral length of a horizontal well, combined with the economic evaluation method. Based on the model proposed by Fan Zifei, Zeng Xiaojing et al. [14] reasonably assumed and simplified the flow of fluid in a reservoir to establish a new model to determine the optimal lateral length of a horizontal well, with the impact of various drilling costs and oil prices fully considered. Hu Junkun et al. [15] established the relationship curve between the net present value and the lateral length of a horizontal well by determining the reasonable production of the gas well and using numerical simulation software to dynamically predict the production capacity of the gas well. They then determined the optimal economic value of the lateral length of the horizontal gas well and conducted a sensitivity analysis of factors such as the formation coefficient, natural gas price, and operating cost. Rammay et al. [16] pointed out that the NPV of a shale-gas horizontal well can be maximized by optimizing the lateral length and hydraulic fracturing operation parameters. Dosummu et al. [17] determined the optimal lateral length and well parameters of a specific reservoir based on the net present value method. They also discussed the impact of crude-oil viscosity, horizontal permeability, and well diameter on the productivity of horizontal wells. Kalantari et al. [18] studied the effects of porosity, permeability, reservoir pressure, production layer thickness, horizontal well length, natural fracture length, and density on shale-gas production by using a numerical simulation method. The above parameters were prioritized with the net-present-value theory and method. Lu Honglin et al. [19] built a model for evaluating the technical and economic limit of the lateral length of a horizontal well in a low-permeability gas reservoir based on the input–output analysis method and discussed the influence of production parameters, gas reservoir parameters, and economic parameters. Based on the productivity prediction of horizontal wells, Wang Dawei et al. [20] and Sun Huachao et al. [21] built a model for evaluating the economic lateral length of a horizontal well under specific parameters, taking into account fixed investments such as drilling and completion, operating costs, and oil and gas sales revenue. The simulation results of an integrated geological and engineering model and the calculation results of economic limit production showed that only gas wells with a horizontal section length of 2000 m could realize economic development, and a single-well EUR had to be more than 154 million cubic meters [22]. He Chang et al. [23,24] used historical production data from the Weiyuan Shale Gas Field to predict future production by analyzing empirical production decline, and then carried out an input–output analysis to obtain the economic lateral length of the horizontal well in the Weiyuan Gas Field. Zhang Jijun et al. [25] optimized the drilling-platform location of a shale-gas multi-well pad based on a digital elevation model and construction cost analysis.

Previous studies have laid an excellent foundation for this study, but there are several problems. (1) The research on the lateral length of shale-gas horizontal wells mainly focuses on two aspects of the technical length: drilling engineering and gas production. (2) Only a few studies focus on the economic lateral length of shale-gas horizontal wells, and they aim to obtain the economic lateral length of horizontal wells in specific gas fields through the statistical analysis of historical production data and economic evaluation, which usually ignore the influence of different hydraulic-fracturing designs [15] and require historical production data from the block [23,24]. This study establishes a universal method for determining the economic lateral length of shale-gas horizontal wells, which considers the impact of hydraulic-fracturing design based on the geological parameters of the blocks. This method does not need to use historical production data and can be used in new shale-gas production areas.

2. Problem Statement and Formulation

In the context of the dual-carbon strategy, oilfield enterprises should accelerate the establishment of a method for optimizing shale-gas development based on geology–engineering–economy integration [26], which will not only reduce the cost but can also keep the energy supply safe and stable [27]. However, scholars have not yet established a clear method for evaluating the economic lateral length of horizontal wells in different shale-gas blocks from the perspective of geology–engineering–economy integration [28], so it is necessary to carry out targeted research to realize the economic development of shale-gas fields, especially new production blocks.

Integrated development is focused on geological research, optimizing the quality of drilling and completion and pursuing optimal economic benefits. Based on previous studies [15,18,23], this paper proposes a method of optimizing the lateral length of shale-gas horizontal wells based on geology–engineering–economy integration. The process (Figure 1) is as follows. Firstly, the geological stratification and formation mechanics parameters are obtained by interpreting the logging curves of the target well with logging software. Secondly, based on the geological and mechanical parameters of the reservoir in the target work area, the Stimplan software developed by NSI is used to simulate the hydraulic-fracture distribution with the actual fracturing process parameters, so the hydraulic fracture half-length and conductivity values under certain fracturing operation parameters can be obtained. Thirdly, the dynamic productivity of shale-gas horizontal wells is predicted using the CMG software developed by the Canada Computer Simulation

Software Group. Fourthly, an input–output analysis of shale-gas horizontal wells is conducted to build a technical–economic evaluation model for the economic lateral length of shale-gas horizontal wells. The economic lateral length is then calculated under specific reservoir, technical, and economic parameters. Lastly, the influence of reservoir geological parameters, technical parameters, and economic parameters on the economic lateral length of horizontal wells is further analyzed and corresponding optimization strategies are given.

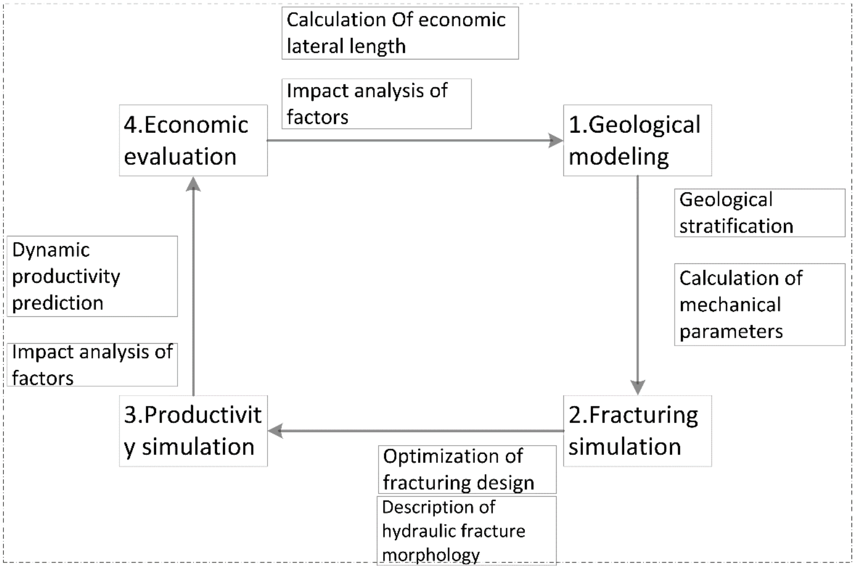

Figure 1. Flow chart detailing the process for the optimization of the lateral length of shale-gas horizontal well based on geology–engineering–economy integration.

3. Model for Evaluating the Economic Lateral Length of Shale-Gas Horizontal Well

In order to establish a model for evaluating the economic lateral length of shale-gas horizontal wells, an input–output analysis is required. The investment in shale-gas horizontal wells mainly refers to the fixed-asset investment in well construction before production, as well as the operation cost and taxes paid after production. The output refers to the revenue from the sales of natural gas, not including the revenue from natural gas by-products.

3.1. Input Analysis

Shale-gas horizontal wells mainly have fixed-asset investments such as drilling, hydraulic-fracturing construction, and surface-engineering construction, as well as operating costs and taxes after production. Drilling and hydraulic fracturing have a great impact on the economic viability of shale-gas horizontal wells [29].

3.1.1. Drilling Investment

For convenience of calculation, referring to previous studies [19,30], the drilling investment is expressed as the drilling length, which is divided into the vertical section, inclined section, and lateral section. The drilling investment of horizontal well is

$$C_d = C_{vd} + C_{sd} + C_{hd} \tag{1}$$

where C_d is the horizontal well-drilling investment, C_{vd} is the drilling investment in the vertical section, C_{sd} is the drilling investment in the inclined section, and C_{hd} is the drilling investment in the lateral section.

Each investment in Formula (1) can be given as an expression related to length.

The drilling investment in the vertical well section can be expressed as Formula (2) and the drilling investment in the inclined section can be expressed as Formula (3).

$$C_{vd} = C_v L_v \quad (2)$$

$$C_{sd} = C_s L_s \quad (3)$$

where C_v is the drilling investment per unit length of the vertical well section, L_v is the length of the vertical section, C_s is the drilling investment per unit length of the inclined section, and L_s is the length of the inclined section.

The drilling-rig rental fee, wage cost, and rotary steering cost increase with the growth of the lateral length of a shale-gas well, as larger lengths require bigger drilling rigs and longer construction periods, leading to an increase in the drilling investment per unit length in the lateral section. To facilitate this calculation, the investment in the horizontal section is expressed as the linear quadratic equation of the length of the horizontal section, namely:

$$C_{hd} = a_0 + a_1 L_h + a_2 {L_h}^2 \quad (4)$$

where a_0, a_1 and a_2 are coefficients and L_h is the lateral length.

Combined with the drilling investment data from 16 typical horizontal wells in the Changning Block with a well depth below 5000 m and expert suggestions, the vertical length is determined to be 3000 m, the unit investment is determined to be 3600 CNY/m, the inclined length is determined to be 1000 m, and the unit investment is determined to be 6000 CNY/m. The values of three constants are fitted using the least-square method, so the relationship between the horizontal section investment and lateral length is as follows:

$$C_{hd} = 1039.78 + 0.21 L_h + 0.0005 {L_h}^2 \quad (5)$$

Since a 50-type drilling rig is generally used for drilling horizontal wells less than 5000 m in depth and a 70-type or even 90-type drilling rig is required for drilling the other ten horizontal wells greater than 5000 m in depth, the investment is increased when compared with a 50-type drilling rig. In this study, the vertical length and inclined length are fixed, so different lateral lengths determine different types of drilling rigs. When $L_h < 900$ m, a 50-type drilling rig is selected; when 900 m $\leq L_h <$ 2500 m, a 70-type drilling rig is selected; and when $L_h \geq 2500$ m, a 90-type drilling rig is selected. Through investment data fitting, it is found that the investment of a 70-type drilling rig is 1.1 times that of a 50-type drilling rig, and the investment of a 90-type drilling rig is 1.3 times that of a 50-type drilling rig. Therefore, the final relationship between horizontal well investment and lateral length is as follows:

$$\begin{cases} C_d = (C_{vd} + C_{sd} + C_{hd}) \times 1.0, L_h < 900 \text{ m} \\ C_d = (C_{vd} + C_{sd} + C_{hd}) \times 1.1, 900 \text{ m} \leq L_h < 2500 \text{ m} \\ C_d = (C_{vd} + C_{sd} + C_{hd}) \times 1.3, L_h \geq 2500 \text{ m} \end{cases} \quad (6)$$

3.1.2. Investment in Hydraulic Fracturing

The number of hydraulic-fracturing sections, sand consumption and liquid consumption will vary with the lateral length. Additionally, the economic lateral length will vary with the half-length and conductivity of the hydraulic fracture. Therefore, referring to the research results of Guo Jianchun et al. [31], the hydraulic-fracturing investment is expressed as the relationship between sand consumption, liquid consumption, and other parameters, as follows:

$$C_f = C_w V_L + C_P Q_{sd} + C_{cz} \quad (7)$$

where C_f is the fracturing investment, C_w is the unit price of the fracturing fluid, V_L is liquid consumption, C_p is the unit price of the proppant, Q_{sd} is sand consumption, and C_{cz} is the cost of the fracturing truck set, packer, perforating gun, and personnel.

In order to facilitate the calculation, using the hydraulic-fracturing investment data of 26 typical wells in Changning Block, the relationship between C_{cz} and fluid consumption is derived so that the hydraulic-fracturing investment can be expressed as

$$C_f = 0.0223V_L + 0.0713Q_{sd} + 0.85 \times 10^{-6}{V_L}^2 + 61.82 \quad (8)$$

3.1.3. Other Investments

The operation cost is directly related to the output, so the operation cost is expressed considering its the relationship with the output. Considering the change in the operation cost per unit output of horizontal wells over time and the benchmark discount rate, the present value of the operation cost of fracturing horizontal wells [19] can be expressed as

$$C_p(t) = \sum_{j=1}^{t} Q_j C_{mg} (1 + r_m)^{j-1} \frac{1}{(1+i)^{j-1}}, \quad (9)$$

where $C_p(t)$ is the net present value of horizontal well operating cost from year one to year t, t is the production life of the horizontal well, C_{mg} is the unit operating cost in the first year, Q_j is the annual output of the horizontal well, r_m is the annual growth rate of the operating cost, and i is the benchmark discount rate.

Comprehensive tax on a shale-gas horizontal well mainly includes the value-added tax, urban maintenance and construction tax, education surcharge, resource tax, and income tax. For the sake of convenience, the comprehensive tax in this paper is expressed as the natural-gas sales revenue multiplied by the comprehensive tax rate, so the net present value of the comprehensive tax for horizontal wells is

$$C_t(t) = CI(t) r_{tax} \quad (10)$$

where $C_t(t)$ is the net present value of comprehensive taxes required for horizontal-well production from year one to year t, $CI(t)$ is the net present value of natural-gas sales revenue from year one to year t, and r_{tax} is the comprehensive tax rate.

According to the estimation of surface-engineering construction investment in Changning Block, the surface-engineering construction investment shared by a single shale-gas well is CNY 1~3 million.

3.2. Output Analysis

In the process of natural-gas production, considering the change in the horizontal well production, natural-gas sales over time, and the benchmark discount rate, the net present value of horizontal-well sales income is

$$CI(t) = \sum_{j=1}^{t} Q_j P \left(1 + C_p\right)^{j-1} \frac{1}{(1+i)^{j-1}} \quad (11)$$

where $CI(t)$ is the net present value of natural-gas sales revenue from year one to year t, Q_j is the annual output of the horizontal well, P is the natural-gas wellhead price in the first year, and C_p is the annual growth rate of the natural-gas sales.

3.3. Evaluation Model of Economic Lateral Length

The cash inflow and outflow of the shale-gas horizontal well are clarified through input–output analysis. The cash inflow is the sales revenue from natural gas produced by the horizontal well. The cash outflow, which is the sum of the fixed-asset investments, operating costs, and the comprehensive taxes of the horizontal well, is as follows:

$$CO(t) = C_d + C_f + C_{dm} + C_p(t) + C_t(t) \quad (12)$$

The NPV is the difference between the cash inflow and the cash outflow of the horizontal well, which is

$$NPV = CI(t) - CO(t) \tag{13}$$

The productivity numerical simulation model, established using the CMG software, can accurately simulate the dynamic productivity of horizontal wells with different lateral lengths under specific hydraulic-fracture half-length and conductivity conditions. Combined with the established model for evaluating the economic lateral length of a shale-gas horizontal well, it can calculate and analyze the change law of the net present value of shale-gas horizontal wells with different lateral lengths. On this basis, the sensitivity analysis method is used to analyze the influence of reservoir geological parameters, technical parameters (production time), and economic parameters on the extreme economic lateral length and the optimal economic lateral length.

4. Calculation Results and Discussion

Due to space limitations, this paper only calculates the economic lateral length of one horizontal well: Well A. It is particularly important to point out that changes in various input parameters will cause changes in the economic lateral length, which can lead to other changes. Well A in Changning Block is a horizontal well in a county in southern Sichuan, located in the south wing of the Ordovician top structure in the Changning anticline structure. The completed well depth is 5000 m, and the artificial bottom is 4950 m, completed with casing and the completed horizon located in the Longmaxi Formation. Table 1 presents a list of geological parameters such as porosity and permeability. Table 2 provides a list of technical parameters such as horizontal-well parameters and production parameters. Table 3 presents a list of economic parameters such as the drilling investment, hydraulic-fracturing investment, and operation cost.

Table 1. Geological stratification results.

No.	VD (m)		MD (m)		Formation Property
	Top	Bottom	Top	Bottom	
1	3333.7	3336.6	3590.2	3600.7	Gas
2	3336.6	3338.7	3600.7	3608.3	Gas
3	3338.7	3339.7	3608.3	3611.8	Gas
4	3339.7	3341.2	3611.8	3615.3	Gas
5	3341.2	3342.8	3615.3	3622.2	Gas
6	3342.8	3345.1	3622.2	3631.5	Gas
7	3345.1	3347.0	3631.5	3645.4	Gas
8	3347.0	3349.9	3645.4	3657.5	Gas
9	3349.9	3351.5	3657.5	3670.0	Gas
10	3351.5	3353.6	3670.0	3789.3	Gas
11	3353.6	3355.9	3789.3	3818.2	Gas
12	3355.9	3358.0	3818.2	3832.5	Gas
13	3358.0	3360.3	3832.5	3975.0	Gas
14	3360.3	3363.8	3975.0	4975.0	Gas

Table 2. Reservoir geological parameters of the shale gas horizontal well.

No.	Parameter Name	Quantity Sign	Unit	Value		
1	Matrix permeability	K	mD	0.0005	0.0010	0.0015
2	Matrix porosity	ϕ	Dimensionless	5.0%	5.6%	6.2%
3	Reservoir thickness	h	m	30	40	50
4	Reservoir temperature	T	K	365.15		
5	Deviation factor of natural gas	Z	Dimensionless	0.87		
6	Relative density of natural gas	γ_g	Dimensionless	0.6		
7	Viscosity of natural gas	μ_g	mPa.s	0.025		

Table 3. Technical parameters of the shale-gas horizontal well.

No.	Parameter Name	Quantity Sign	Unit	Value		
1	Production time	t	year	6	8	10
3	Production differential pressure	ΔP	MPa	3	5	7
4	Vertical length	L_v	m	3000		
5	Inclined length	L_s	m	1000		
6	Lateral length	L_h	m	100~3600		
7	Cluster spacing	L_c	m	20		
8	Number of perforating clusters	S_{pf}	cluster	3		
9	Well control radius	R_e	m	400		

4.1. Calculation Example

4.1.1. Geological Modeling

Logging software is used to interpret the density (DEN), compression wave (DTC), shear wave (DTS), and natural gamma ray (GR) logging curves of Well A so that geological stratification can be conducted, which is shown in Table 1. The static Young's modulus (E), Poisson's ratio (PR), and in situ stress (STRESS) are calculated using a built-in program, which will be used in subsequent fracturing simulations.

4.1.2. Fracturing Simulation

The lateral length of the horizontal well is 1250 m, 1200 m of which will be fractured, and the thickness of the reservoir is approximately 20 m. The Stimplan software is used for fracturing simulation. The length of a single fracturing section is 60 m, the number of fracturing sections is twenty, the number of perforation clusters in each section is three, and the cluster spacing is approximately 20 m. The average half-length of the fracture is 180 m and the conductivity is 300 mD · m under the pumping procedure conditions of 1364.7 m^3 liquid consumption and 467.1 t sand consumption in a single section. The hydraulic-fracture morphology in a single fracturing section is shown in Figure 2.

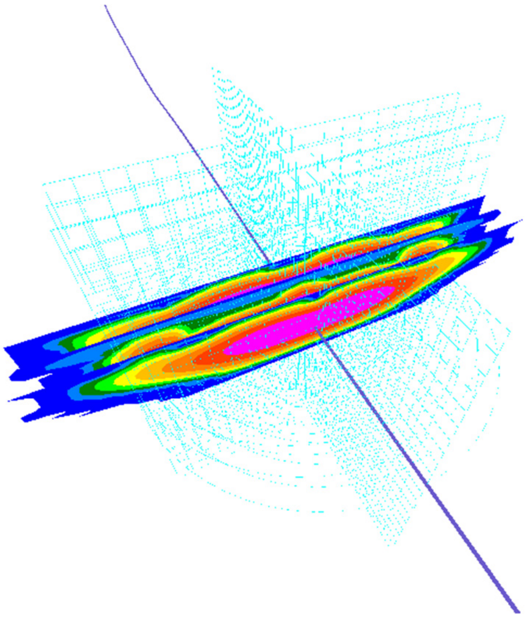

Figure 2. The hydraulic-fracture morphology in a single fracturing section.

4.1.3. Capacity Simulation

The CMG software is used to simulate the productivity of shale-gas horizontal wells with a horizontal lateral length ranging from 100 m to 3600 m.

4.1.4. Calculation of the Economic Lateral Length

The net present value of a shale-gas horizontal well with a specific lateral length is calculated using the methodology shown in Figure 3, with the second parameter in the "parameter value" field in Tables 2–4 [16,19]. The above process is repeated to obtain the relationship curve between the NPV of the shale-gas horizontal well and its lateral length, as is shown in Figure 4. The average half-length of the fracture is 180 m and the conductivity is 300 mD · m.

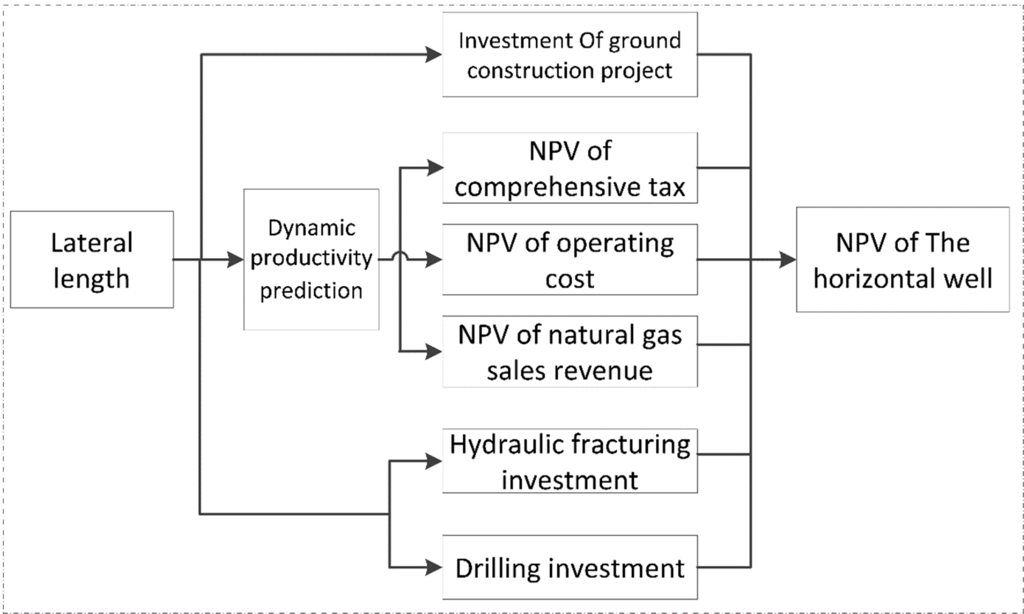

Figure 3. Calculation methodology used to find the net present value of a horizontal well with a specific lateral length.

Table 4. The economic parameters of the shale-gas horizontal well.

No.	Parameter Name	Quantity Sign	Unit	Value		
1	Natural-gas wellhead price	P	CNY/m^3	1.159	1.275	1.402
2	Annual growth rate of natural-gas wellhead price	C_p	Dimensionless	5%	10%	15%
3	Benchmark discount rate	i	Dimensionless	6%	8%	10%
4	Investment in surface engineering construction	C_{dm}	10^4 CNY	100	200	350
5	Unit drilling investment in vertical section	C_v	10^4 CNY/m		0.36	
6	Unit drilling investment in inclined section	C_s	10^4 CNY/m		0.60	
7	Unit drilling investment in lateral section	C_h	10^4 CNY		Equation (6)	
8	Unit operating cost in the first year	C_{mg}	CNY/m^3	0.125	0.138	0.152
9	Annual growth rate of operating cost	r_m	Dimensionless	5%	10%	15%
10	Comprehensive tax rate	r_{tax}	Dimensionless	8%	10%	12%
11	Hydraulic-fracturing investment	C_f	10^4 CNY		Equation (8)	

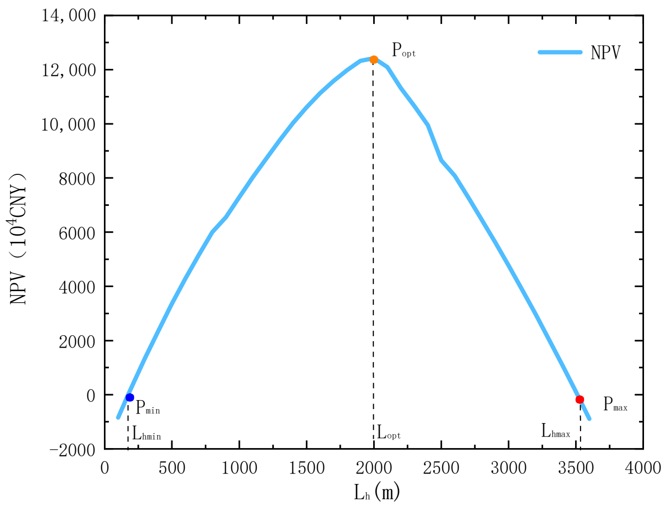

Figure 4. Relationship curve between the NPV and lateral length when the half-length of the fracture is 180 m.

Figure 4 has three points: P_{min}, P_{opt}, and P_{max}. The NPV corresponding to the P_{min} point is 0, and the corresponding lateral length is the minimum extreme economic length L_{min}, which is 175 m. The NPV corresponding to the P_{max} point is 0, and the corresponding lateral length is the maximum extreme economic length L_{max}, which is 3508 m. The NPV corresponding to the P_{opt} point is the largest, and the corresponding lateral length is the optimal economic length L_{opt}, which is 2000 m. The selection range of the actual lateral length is 175 m $\leq L \leq$ 3518 m under the parameters used in this example. The lateral length of the 336 production wells in Changning Block range from 800 m to 3500 m [32], which confirms the accuracy of this study to some extent.

The optimal lateral length is largely dependent on the hydraulic-fracturing design. Therefore, the effects of a change in the economic length of the horizontal section are investigated, when the half-length of the hydraulic fracture is 300 m and the conductivity is 300 mD $\cdot$ m, as is shown in Figure 5. The optimal lateral length is still 2000 m long, but the minimum extreme economic length decreases and the maximum extreme economic length increases. The increase of the half-length of the hydraulic fracture increases the optional range of the economic lateral length.

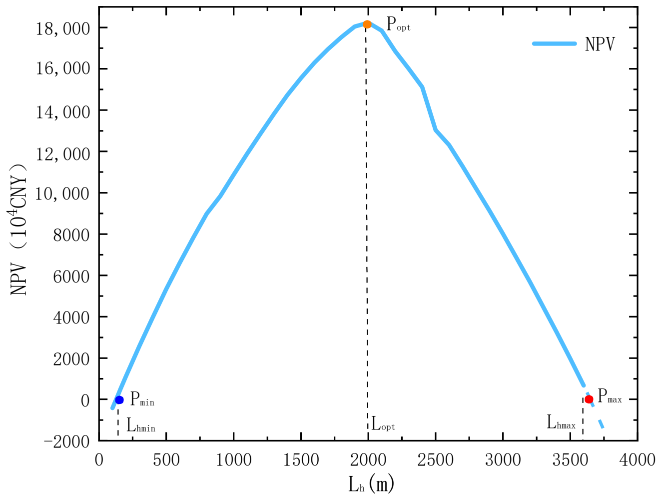

Figure 5. Relationship curve between the NPV and the lateral length when the half-length of the fracture is 300 m.

4.2. Sensitivity Analysis and Discussion

The control variable method is adopted to study the influence of six factors on the economic lateral length, including reservoir matrix porosity, thickness, production time, drilling investment, natural-gas wellhead price, and benchmark discount rate. The results are shown in Figure 6.

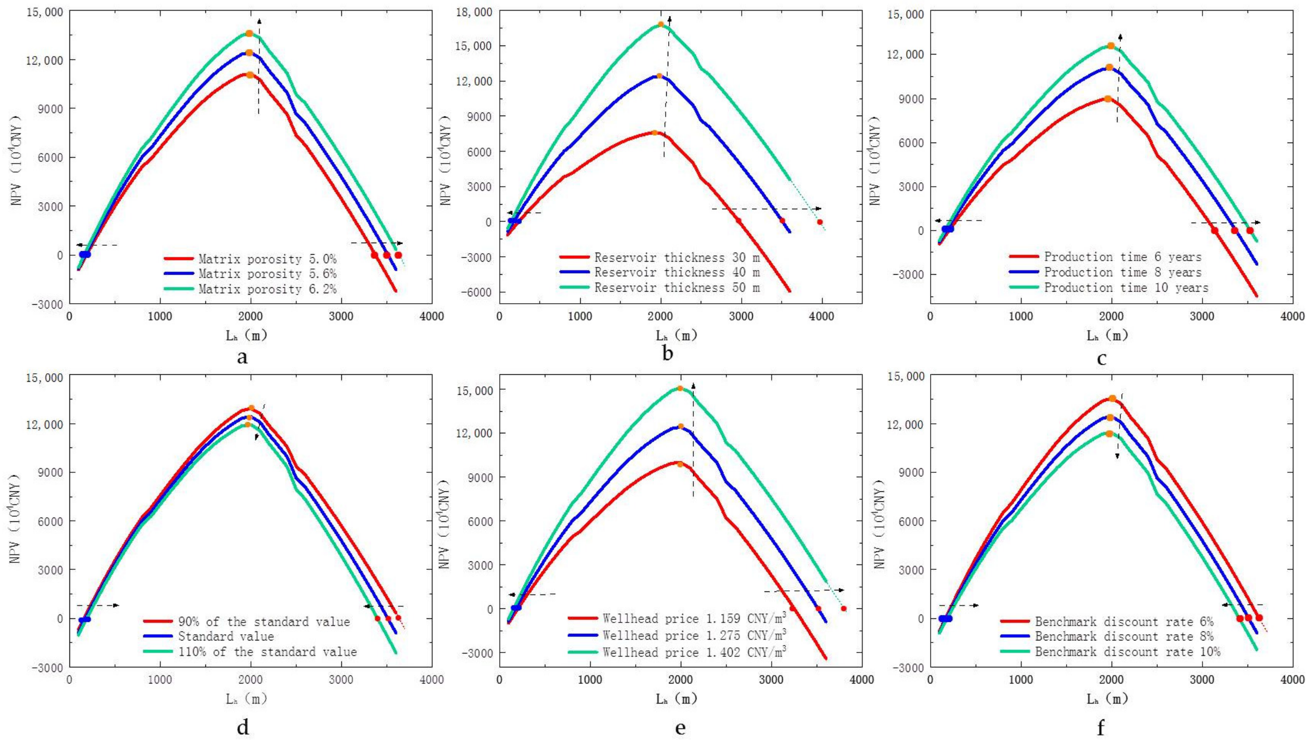

Figure 6. Relationship curves between the NPV and lateral length of a shale-gas horizontal well with six changing factors. (**a**) the relationship curve between the NPV and lateral length with different matrix porosities; (**b**) relationship curve between the NPV and lateral length with different reservoir thicknesses; (**c**) relationship curve between the NPV and lateral length with different production time; (**d**) relationship curve between the NPV and lateral length with different drilling investment values; (**e**) relationship curve between the NPV and lateral length with different wellhead prices; and (**f**) relationship curve between the NPV and lateral length with different benchmark discount rates.

4.2.1. Sensitivity Analysis of Reservoir Matrix Porosity

Generally speaking, the production of a shale-gas horizontal well increases with an increased reservoir matrix porosity, which means that a shorter lateral length is more economical. At the same time, the maximum extreme economic lateral length will also increase because the increase in production is enough to offset the increase in drilling and completion investment. Figure 6a shows that, with an increase in reservoir matrix porosity, the curve moves to the upper right, the minimum extreme economic lateral length decreases, the maximum extreme economic lateral length increases, and the economic benefits of a horizontal well with the same lateral length improve.

4.2.2. Sensitivity Analysis of Reservoir Thickness

There is a strong positive correlation between the productivity of a shale-gas horizontal well and its reservoir thickness. Therefore, an increase in reservoir thickness improves the economic benefits of horizontal wells with a shorter lateral length. Figure 6b shows that, with an increase in reservoir thickness, the curve moves to the upper right, the minimum extreme economic lateral length decreases, the maximum extreme economic lateral length increases, and the economic benefits of a horizontal well with the same lateral length improve.

4.2.3. Sensitivity Analysis of Production Time

Both production practice and academic research show that 20 years is a reasonable evaluation period for a shale-gas horizontal well [33]. The economic viability of a horizontal well with the same lateral length increases with production time, which leads to a larger range of lateral length. Figure 6c shows that, with an increase in production time, the curve moves to the upper right, the minimum extreme economic lateral length decreases, the maximum extreme economic lateral length increases, and the economic benefits of horizontal well with the same lateral length improve.

4.2.4. Sensitivity Analysis of Drilling Investment

Production is certain for a horizontal well with a specific lateral length. An increase in drilling investment indicates worsening economic benefits, leading to a smaller range of lateral length. Figure 6d shows that, with increasing drilling investment, the curve moves to the lower left, the minimum extreme economic lateral length increases, the maximum extreme economic lateral length decreases, and the economic benefits of a horizontal well with the same lateral length worsen.

4.2.5. Sensitivity Analysis of Natural-Gas Wellhead Price

For a horizontal well with a specific lateral length in a specific reservoir, the production is certain. An increase in the natural-gas wellhead price means an increase in the gas sales revenue, which makes the horizontal well more economical and leads to a larger range of lateral length. Figure 6e shows that with an increase in production time the curve moves to the upper right, the minimum extreme economic lateral length decreases, the maximum extreme economic lateral length increases, and the economic benefits of horizontal well with the same lateral length improve.

4.2.6. Sensitivity Analysis of Benchmark Discount Rate

The benchmark discount rate represents the expected return on investment of the project. In terms of the investment in a shale-gas horizontal well, a high-benchmark discount rate will lead to a smaller range of lateral length, while a low-benchmark discount rate will lead to a larger range of lateral length. Figure 6f shows that, with an increase in the benchmark discount rate, the curve moves to the lower left, the minimum extreme economic lateral length increases, the maximum extreme economic lateral length decreases, and the economic benefits of the horizontal well with the same lateral length worsen.

Table 5 shows the minimum extreme economic lateral length, the maximum extreme economic lateral length, and the optimal economic length under different factors. The influence of the natural-gas wellhead price in the first year, the reservoir thickness, matrix porosity, production time, drilling investment, the benchmark discount rate on the economic lateral length, and the economic benefits of the horizontal well are weakened in turn.

Table 5. Economic lateral length of the horizontal well with six changing factors.

No.	Parameter	Value	Minimum Extreme Economic Length/m	Maximum Extreme Economic Length/m	Optimal Economic Length/m
1	Matrix porosity	5%	189	3373	1993
		5.6%	175	3508	2000
		6.2%	165	3633	2004
2	Reservoir thickness	30 m	238	2972	1875
		40 m	175	3508	2000
		50 m	142	3962	2009
3	Production time	6 years	203	3143	1957
		8 years	178	3350	1984
		10 years	175	3508	2000
4	Drilling investment	90% of the standard value	159	3635	2015
		Standard value	175	3508	2000
		110% of the standard value	191	3398	1980
5	Natural-gas wellhead price	1.159 CNY/m^3	201	3229	1986
		1.275 CNY/m^3	175	3508	2000
		1.402 CNY/m^3	154	3787	2012
6	Benchmark discount rate	6%	165	3626	2014
		8%	175	3508	2000
		10%	186	3408	1987

5. Conclusions

The lateral length of horizontal wells is an important parameter in shale-gas development. Advances in engineering technology, the optimization of management measures, and changes in the natural-gas wellhead price will alter the economic lateral length and the economic benefits of horizontal wells. Therefore, it is necessary to adhere to the idea of geology–engineering–economy integration and take the following measures to optimize lateral length.

Applying the theory of technical economics to conduct interdisciplinary research with the aim of achieving optimized engineering technical parameters and management measures is a practical way to reduce costs and increase the efficiency of oil and gas enterprises, especially as drilling technology and reservoir-stimulation technology in petroleum engineering have peaked and revolutionary breakthroughs are rare. The optimal lateral length of horizontal wells in Changning Block is 175~3508 m and the optimal economic length is 2000 m under the current geological understanding, engineering technology and production-management level. The R&D of drilling technology and management optimization should be a point of focus to further improve drilling engineering and to reduce drilling investment. On one hand, we should actively pursue the continuous improvement of technology to achieve technical breakthroughs and continue to tackle the key problems that long horizontal sections present to drilling technologies, especially issues with geological-steering and rotary-steering technologies, environmentally friendly anti-collapse drilling fluids, the reduction of drilling accidents, and an improvement in penetration rates. On the other hand, the batch drilling mode of well plants should be further promoted, and the construction links should be optimized according to the drilling investment list. We should promote the marketization reform of natural-gas prices and reasonably increase the price of natural gas in non-livelihood areas through the reasonable evaluation of the contribution of shale gas to the "dual-carbon" strategy. Subsidies should be established considering the price of shale gas in high-risk blocks or upstream production blocks to maintain competitive shale-gas wellhead prices and a certain annual growth rate.

This article discusses a method for optimizing the economic lateral length of shale-gas horizontal wells. However, there are still several factors that have not been considered, such as reservoir heterogeneity, early exploration investment, and workover investment. Moreover, only a single-factor sensitivity analysis has been carried out, which cannot fully meet the actual requirements on-site. The estimation of drilling investment and hydraulic-fracturing investment is relatively rough, affecting the accuracy of the economic length of the horizontal section. Therefore, a multifactor sensitivity analysis should be conducted and the drilling investment and hydraulic-fracturing investment should be refined in the next step to further improve engineering practices.

Author Contributions: Conceptualization, S.H. and J.Z.; methodology, software, validation, J.Z.; formal analysis, investigation, L.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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