processes

MDPI

Article

Optimization of Energy Consumption in Oil Fields Using Data Analysis

Xingyuan Liang, Zhisheng Xing, Zhenduo Yue, He Ma, Jin Shu and Guoqing Han *

College of Petroleum Engineering, China University of Petroleum (Beijing), 18 Fuxue Road, Changping, Beijing 102249, China; xyliang@cup.edu.cn (X.L.); xingzhisheng0214@163.com (Z.X.)
* Correspondence: cup_706ac@163.com

Abstract: In recent years, companies have employed numerous methods to lower expenses and enhance system efficiency in the oilfield. Energy consumption has constituted a significant portion of these expenses. This paper introduces a normalized consumption factor to effectively evaluate energy consumption in the oilfield. Statistical analysis has been conducted on nearly 45,000 wells from six fields in China. Critical factors such as lifting method, daily production, pump depth, gas–oil ratio (GOR), and well deviation angle were evaluated individually. Results revealed that higher production could lead to lower normalized consumption for beam pumps, progressive cavity pumps, and electric submersible pump systems, thus enhancing system efficiency. Additionally, a higher GOR might result in lower normalized consumption for the beam pump system, while the deviation angle of the well showed negligible impact on the normalized consumption factor. This manuscript offers a method to assess the impacts of artificial lift methods on production and discusses suggestions for reducing consumption associated with each lifting method in the oilfield.

Keywords: energy consumption; system efficiency; beam pump; progressive cavity pump; electric submersible pump

check for updates

Citation: Liang, X.; Xing, Z.; Yue, Z.; Ma, H.; Shu, J.; Han, G. Optimization of Energy Consumption in Oil Fields Using Data Analysis. *Processes* **2024**, *12*, 1090. https://doi.org/10.3390/pr12061090

Academic Editor: Peter Glavič

Received: 16 April 2024
Revised: 20 May 2024
Accepted: 23 May 2024
Published: 26 May 2024

1. Introduction

Oil production is contingent upon reservoir pressure during the initial production phase. In instances where reservoir pressure is insufficient, artificial lift methods are implemented to facilitate oil extraction [1–4]. Artificial lift methods are designed to provide the necessary energy for oil extraction. These methods encompass various techniques, including beam pumps, progressive cavity pumps, electric submersible pumps, and gas lifts [5–7]. Due to limited gas resources, the gas lift method has been restricted in China. Consequently, the other three methods serve as the primary means of facilitating oil production. Each of these methods utilizes distinct types of mechanical equipment. Despite significant advancements in artificial lift technologies in recent years, system efficiency remains relatively low, particularly for the beam pump system [8,9]. The lower system efficiency leads to huge energy consumption in the field, which also affects oil production [10–14]. Due to the low prices of oil, companies are starting to reduce expenses and improve oil production and efficiency [15–22]. There are over 920,000 operating wells in the world [23–26], and 87% of them are producing oil with artificial lift methods [27,28]. Methods have been proposed to reduce energy consumption in the oil field.

A new, comprehensive simulator was developed to optimize the efficiency of the pump unit system. The authors provided an improved prediction for power requirements and obtained a good agreement [25,29]. A new intelligent tracking software for the pump (ESP) system has been developed to reduce energy consumption [30]. The authors have set up a variable-speed drive unit to optimize operation conditions [31]. Zhang et al. have also developed a quick solution to optimize the oil block. The method has been used in the Daqing field in China, and the total energy consumption has decreased by

16% [19]. Sanchez has presented practical and theoretical benefits obtained with the inclusion of rod pump controllers in beam pump systems. The controllers can not only decrease energy consumption and expenses but also optimize production and manpower utilization [32]. Sun has determined the factors affecting energy consumption; besides, the energy analysis and forecasting network model have been constructed by an artificial neural network algorithm [33,34]. Wang et al. have presented the innovative energy-saving rebuilding techniques used in the Daqing field in detail. These techniques improved the efficiency of beam pump systems after application to more than 2000 producers [35,36]. Xing et al. have put forward a new complex simulation method of efficiency optimization for the sucker-pump unit system [25]. The model has been built to predict and optimize the power requirements. The results are good, especially in high stroke frequency and small-diameter pumps. However, these methods are either complex or circumscribed. Kindi et al. [37–40] collected ESP parameter data and energy consumption readings from approximately 250 wells and employed data analytics and Six Sigma tools to analyze the primary factors influencing ESP system energy consumption while simultaneously establishing optimization models to reduce ESP system energy consumption. The results indicate that the use of this system can save approximately USD 3.0 million in operational costs annually and reduce CO_2 emissions by 5500 tons.

Qualitative analysis is adopted in the above articles, and the conclusions are all aimed at a certain oilfield or block, and there is no general analysis of influencing factors. In this paper, nearly 45,000 wells in major oil fields in China were analyzed based on a novel parameter, termed the normalized consumption factor, which can be readily obtained to illustrate the factors affecting energy consumption. By this method, the general law of the impact of various factors, including lifting method, pump depth, daily production, gas–oil ratio (GOR), and well deviation angle, on the energy consumption of the extraction system was investigated, which has certain guiding significance for energy conservation in oil fields. Additionally, recommendations for addressing the issue were explored for each factor in the oil field.

2. Method

At present, there are three kinds of artificial lifting systems commonly used in oil fields, i.e., beam pump artificial lifting systems, progressive cavity pump artificial lifting systems, and electric submersible pump (ESP) artificial lifting systems. Among them, owing to its high reliability, durability, simple structure, and ease of manufacture, the beam pump system has remained the primary production method in China [13]. The beam pump system is usually powered by the power engine; the high-speed rotation of the power engine is changed into the low-speed rotation of the pumping unit crank by the reducer; the rotating motion is changed into the upper and lower reciprocating movements of the pumping unit donkey head by the crank-connecting rod; and the deep well pump is driven by the suspension rope assembly. When the beam pump system is running, the load change of the downhole pumping pump, which works with the pumping unit, will cause a work imbalance in the system, which will increase the reactive power consumption of the power system and lead to the low efficiency of its operation, resulting in a huge waste of energy. The progressive cavity pump artificial lifting system has the characteristics of high efficiency and energy savings and is mainly composed of two parts, i.e., the ground drive device and the downhole progressive cavity pump. The downhole progressive cavity pump is composed of a stator and a rotor. When the rotor moves in the stator, the rotor and the stator mesh form a series that is 180° apart. With the rotation of the rotor, the sealing cavity moves axially from the suction end of the pump to the discharge end. As a positive displacement pump, a progressive cavity pump is characterized by its simple structure, small size, and light weight; there will be no pump card, gas lock, sand wax, or other blockage; it will not form an emulsion. An electric submersible pump artificial lifting system is downhole lifting equipment that puts the motor and pump together below the liquid level in the oil well to pump oil. The ground power supply transmits electric energy to the downhole submersible motor through the transformer, control screen, and cable, so that the motor drives the multi-stage centrifugal pump to rotate the electric energy into mechanical energy and lift the oil to the ground. In recent years, electric submersible pump lifting technology has developed rapidly. In oil field production, especially in the high water cut period, most of the crude oil is produced by an electric submersible pump. The electric submersible pump will play an important role in the lifting technology of non-flowing high-yield wells or wells with high water content. The economic operation area of the electric submersible pump artificial lifting system is generally selected to be between 60% and 135% of the rated displacement. When the machine and pump are not configured so that the displacement deviates from the high-efficiency area, the overall efficiency of the electric submersible pump will significantly decrease, resulting in an increase in energy consumption for the electric pump.

Based on the normalized consumption factor, a database comprising nearly 45,000 wells from six fields in China was analyzed. These fields include Changqing Oilfield (located in Yan'an, Shaanxi Province, China), Daqing Oilfield (located in Daqing, Heilongjiang Province, China), Jilin Oilfield (located in Jilin, Jilin Province, China), Huabei Oilfield (located in Renqiu, Hebei Province, China), Jidong Oilfield (located in Tangshan, Hebei Province, China), and Turpan–Hami Oilfield (located in Turpan, Xinjiang Uygur Autonomous Region, China). In view of the complex geological characteristics of China's oil fields, beam pumps, progressive cavity pumps, and electric submersible pump systems play their respective advantages under different geological conditions and field sizes, helping the oil fields achieve stable production and efficient oil recovery operations. Among them, Changqing Oilfield is located in the Shaanxi Basin, with a complex geological structure and diversified reservoirs, most of which have high viscosity, high sulfur content, and high sand content. It is one of the most widely used oilfields for progressive cavity pump production in China. Huabei Oilfield is abundant in oil resources, but most oil wells have low output and high water content, which is suitable for electric submersible pump production. Most of the oil wells in Daqing oilfield are old ones with low production capacity and complex geological conditions, so the beam pump is the main oil production method suitable for Daqing oilfield. However, with the continuous expansion of the development and production scale of oil fields, the energy consumption of oil production has become increasingly prominent.

The energy consumption of the several pump systems mentioned above comprises two components. The first component is electrical power, which is utilized for lifting the liquid, while the second component is the friction loss incurred by the equipment during operation. Friction loss encompasses motor loss, belt and gearbox friction, friction between the rod and packing box, friction between sucker rod and tubing, friction between liquid and sucker rod, friction between liquid and tubing, as well as pump energy loss.

Currently, energy consumption is commonly employed to calculate the energy consumption of individual wells or blocks of wells, while system efficiency is utilized to assess the overall performance of a well. However, as power consumption varies with the depth of wells—meaning deeper wells require more energy consumption—the normalized consumption factor (C_n) was introduced to mitigate the influence of well depth and accurately evaluate the consumption factor. By analyzing the relationship between pump system efficiency and mechanical consumption, a mathematical formula 1–3 was derived. Results such as system efficiency can be obtained through field instrument testing, and then normalized results can be obtained through formula calculation.

$$C_\mathrm{n} = \frac{P_\mathrm{E} \cdot T}{Q \cdot \frac{H}{100}} \tag{1}$$

$$P_\mathrm{E} = \frac{P'}{\eta} = \frac{1000 \cdot Q \cdot H \cdot 9.8}{86400 \cdot \eta}(\mathrm{W}) \tag{2}$$

$$C_n = \frac{100,000 \cdot 9.8}{\eta \cdot 1000 \cdot 3600}(\text{kW} \cdot \text{h}/(\text{t} \cdot 100\text{m})) = \frac{0.2723}{\eta}(\text{kW} \cdot \text{h}/(\text{t} \cdot 100\text{m})) \quad (3)$$

Figure 1a depicts the correlation between production and system efficiency for the beam pump system. As observed in the figure, describing the relationship between production and system efficiency is challenging. However, upon normalizing the data, as illustrated in Figure 1b, the trend becomes readily discernible. It is evident that the normalized consumption factor decreases with increasing daily production. When the normalized consumption factor approaches 1, energy consumption is minimized, corresponding to higher system efficiency.

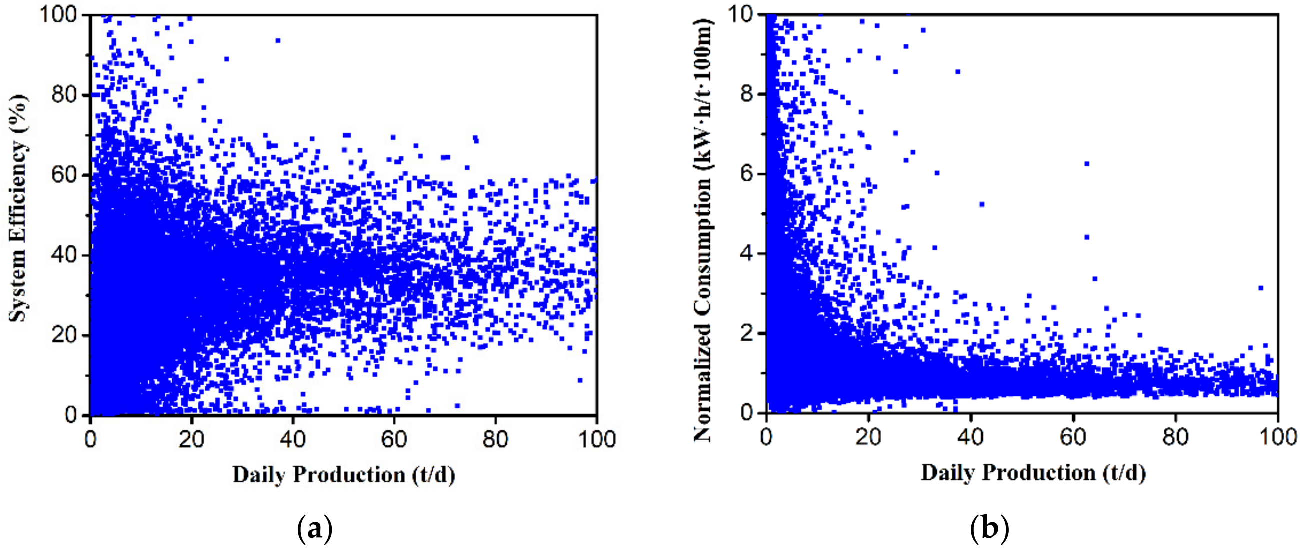

Figure 1. Comparison before and after normalization. (**a**) Before normalization; (**b**) After normalization.

As depicted in Figure 2, there are 42,250 wells utilizing the beam pump system, accounting for 94.38% of the total wells. Additionally, the beam pump system boasts rich management experience. However, its weight renders dismounting and movement inconvenient [41]. The beam pump system is suitable for shallow and moderately deep wells but unsuitable for sloped or offshore wells. Moreover, it is ill-suited for wells with high sand content, wax deposits, elevated salinity levels, or heavy oil [3,42]. There are 2212 wells utilizing the progressive cavity pump system, accounting for 4.94% of the total wells. In comparison to the beam pump system, the progressive cavity pump system entails lower initial investment and maintenance expenses. It is commonly employed in offshore wells and is well-suited for wells containing heavy oil, sand, or exhibiting a high gas–oil ratio (GOR) [43]. However, the rubber stator is more susceptible to damage, leading to increased maintenance requirements. Additionally, improper operation can result in pump failure. The electric submersible pump system is employed in only 304 wells, comprising 0.68% of all wells. It is preferred for high-production wells due to its ease of operation and management. Furthermore, it is suitable for use in sloped or offshore wells, as well as in wells with heavy oil [44–46]. However, its cost and maintenance are high. The electrical machinery and cables are prone to breakdowns [47].

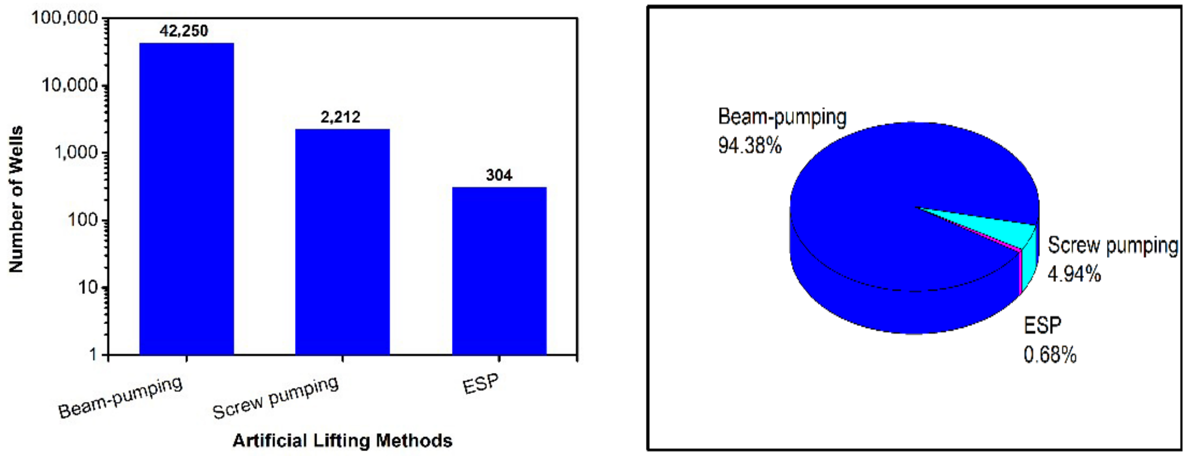

Figure 2. Distribution of lifting methods.

3. Results and Discussion

Because the data we collected did not include offshore wells, the wells equipped with beam pump systems account for a significant proportion. Drawing from this dataset, the influence of lifting methods, production rates, pump depths, gas–oil ratios (GOR), and well angles was analyzed.

3.1. Beam Pump System

The beam pump system mainly consists of two parts: the ground pump unit and the underground pump system [48]. The energy consumption mainly contains mechanical fractional loss and useless work during the operation period, as well as the unbalance of the ground system [49,50].

3.1.1. Impact of Daily Production on the Normalized Consumption Factor

Due to noisy data points, normalized consumption factors exceeding 10 kW·h/(t·100 m) were excluded. A total of 42,250 wells were analyzed, accounting for nearly 95% of the entire database. From Figure 1b, it can be inferred that the normalized consumption factor gradually decreases with increasing daily production. Particularly when daily production is less than 10 t/d, the normalized consumption factor is higher. Conversely, the normalized consumption factor decreases slowly with increasing daily production when production exceeds 10 t/d. Unfortunately, the production for a total of 31,900 wells is less than 10 t/d, indicating the need to develop methods to reduce energy consumption for wells with high normalized consumption factors. To further elucidate the trend, the data were divided and simplified. Data were categorized into ranges of 5 t/d increments, such as 0–5, 5–10, 10–15, 15–20, 20–25, 25–30, and 30–35 t/d, respectively, and the average value within each range was determined. As illustrated in Figure 3, consumption decreases rapidly with increasing production up to 15 t/d.

A significant portion of energy consumption is attributed to the imbalance between the beam pump and the electric motor [51]. Because the load varies between the upstroke and downstroke, whereas the electric motor is designed for constant load, the motor's performance does not align with that of the beam pump, resulting in inefficiency. A prevalent occurrence in the field is that the motor's rated power is high while the actual load is low, leading to reduced motor efficiency [52,53]. Based on the correlation between motor loading rate and pump efficiency, it is observed that when the motor loading rate is less than 20%, motor efficiency increases rapidly with enhanced loading. However, when the motor load exceeds 20%, the rate of increase in motor efficiency slows down. Furthermore, when the motor load surpasses 40%, motor efficiency stabilizes at 90% with increasing loading [19,54]. Additionally, production parameters such as pump size, length, and stroke frequency can influence power consumption. Larger pump diameters, greater lengths, and increased stroke frequencies tend to result in decreased power consumption, with these parameters correlating to higher production rates. Consequently, the normalized consumption factor decreases with higher production, particularly when production levels are low.

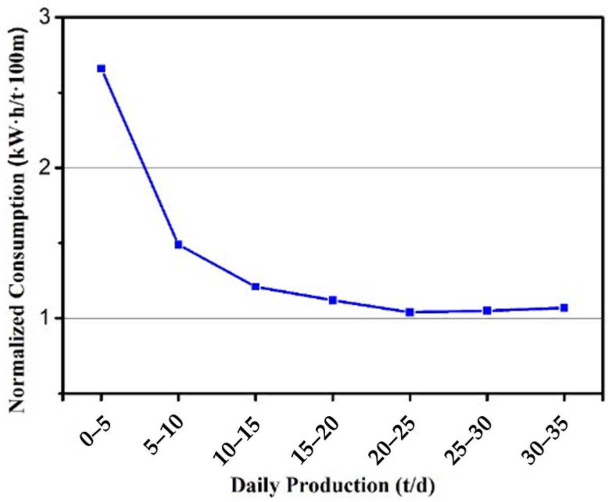

Figure 3. Simplified relationship between daily production volume (divided by production fluid volume) and normalized consumption.

As depicted in Figure 4, the depth of wells equipped with the beam pump system is predominantly less than 2500 m. The majority of wells exhibit a normalized consumption factor lower than 5 kW·h/t·100 m. However, wells with pump depths around 1500 m tend to have higher normalized consumption factors compared to other depths. This could be attributed to the increased submergence associated with higher pump depths, which may correspond to higher production rates. Based on these findings, it is evident that high production is conducive to reducing the normalized consumption factor, resulting in relatively lower values. Conversely, for shallower pump depths, friction is significantly reduced, thereby lowering the normalized consumption factor. Some data points within the high normalized consumption factor range originate from a specific area, suggesting that management practices in that area may contribute to the higher values.

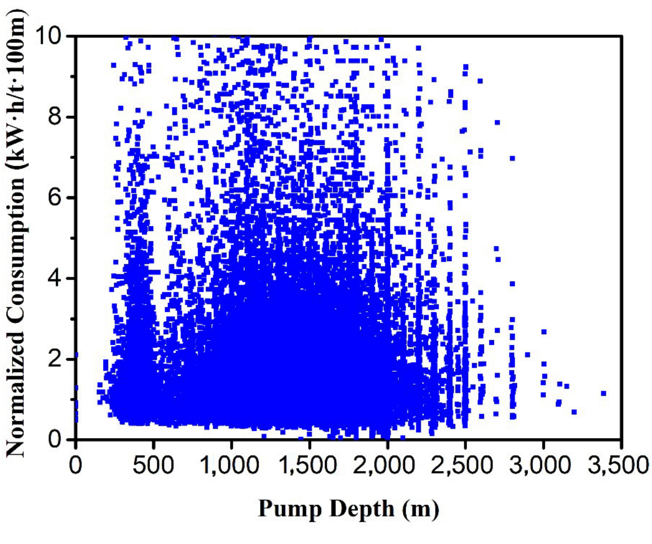

Figure 4. Impact of pump depth on the normalized consumption factor for beam pump systems.

For the points in the area of the high normalized consumption factor, people have developed many methods to reduce energy consumption, including reducing the balance material and exchanging a lighter rod. Because the motor is the power resource of the beam pump, the working situation of the beam pump is decided by the reliable motor. In order to save more energy, engineers should choose a motor with high efficiency that can use the transducer to control power consumption with load variation. Nonetheless, the beam pump system is being replaced by another energy-saving pump unit. For example, the bending beam and digital pump unit are expanding in the Changqing oil field in China.

3.1.2. Impact of Gas–Oil Ratio (GOR) on Normalized Consumption Factor

As depicted in Figure 5, there is a slight decrease in the normalized consumption factor with an increasing gas–oil ratio (GOR). Wells with a GOR of less than 10 m^3/m^3, considered non-gas-producing wells, were excluded from the analysis, resulting in a total of 9523 wells analyzed. This result can be attributed to two main factors. Firstly, the fill level of the pump, which is positively correlated with pump efficiency, decreases as GOR increases. Pump efficiency, a crucial component of overall system efficiency, is influenced by factors such as friction between the plunger and bush, leakage, hydraulic losses, and the fill level [40,55]. Hence, a higher GOR may correspond to a higher normalized consumption factor. However, friction can significantly decrease with increasing GOR, and friction is another key factor in the normalized consumption factor. Friction between the rod and the liquid can increase load and power consumption. On one hand, as the amount of liquid decreases, friction is reduced. On the other hand, increasing viscosity can dramatically increase friction [56,57]. However, viscosity tends to decrease after mixing with gas. Taking into account both of these effects, the normalized consumption factor decreases with increasing GOR.

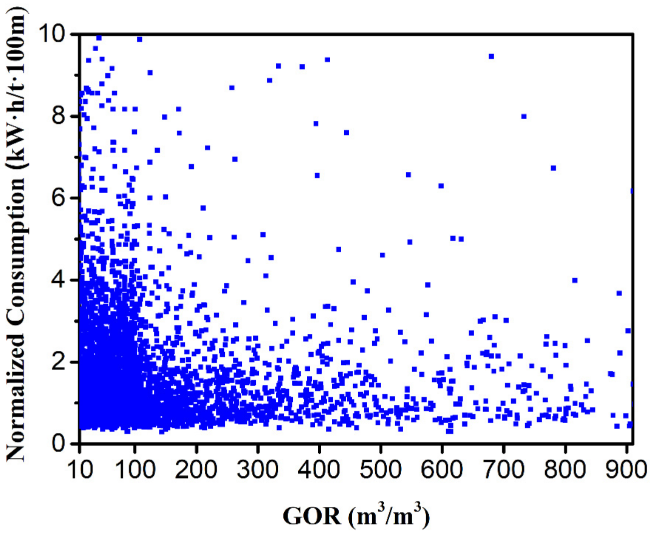

Figure 5. Impact of GOR on the normalized consumption factor for beam pump systems.

3.1.3. Impact of Well Angle on the Normalized Consumption Factor

Wells with an angle of less than 5° are considered vertical wells and were not included in the analysis. A total of 8522 wells were analyzed. As depicted in Figure 6, there is no significant variation in the normalized consumption factor with increasing well angle, indicating that well angle does not significantly impact consumption. This can be attributed to two main factors. Firstly, as the well angle increases, friction between the rod and tube may increase, resulting in reduced efficiency and increased energy consumption. Conversely, the axial load decreases with increasing angle, which can reduce the load and increase system efficiency. Additionally, stabilizers are commonly installed in most wells, further reducing friction between the tube and rod. These combined effects result in no discernible difference in the normalized consumption factor. The density of points suggests that a large number of wells exhibit lower normalized consumption factors.

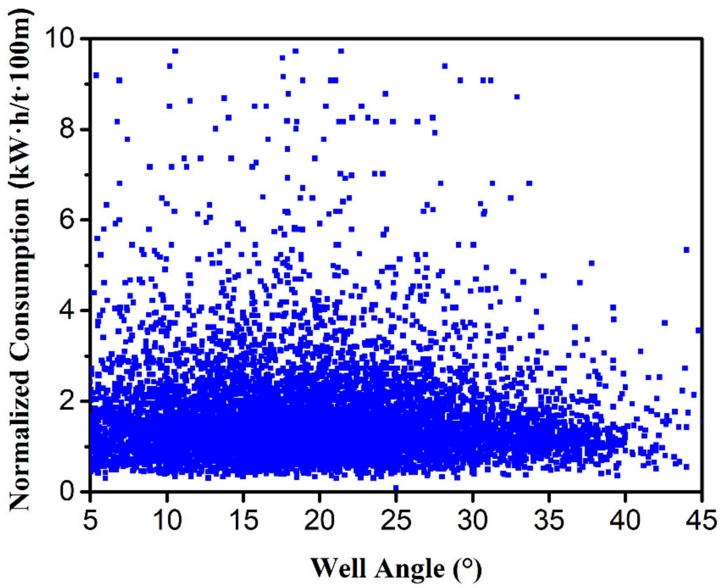

Figure 6. The impact of well angle on the normalized consumption factor for beam pump systems.

3.2. Progressive Cavity Pump System

The progressive cavity pump is a highly efficient lifting method, primarily comprising a ground and downhole screw driving device. Due to its relatively small size, the progressive cavity pump consumes less power [58]. Nevertheless, energy consumption induced by friction remains considerable. This energy consumption primarily stems from mechanical frictional losses between the rotor and pipe wall during operation. Additionally, the high maintenance costs can further inflate operational expenses. Figure 7 illustrates the analysis of 2212 progressive cavity pump wells. Compared to the production data for the beam pump system shown in Figure 1b, Figure 7 displays fewer noisy data points, indicating that the trend for the progressive cavity pump method is clearer than that for the beam pump method. Moreover, for most wells with a daily production exceeding 20 t/d, the normalized consumption factor is less than 1 kW·h/t·100 m. This suggests that energy consumption is relatively lower than that of the beam pump system [59–63].

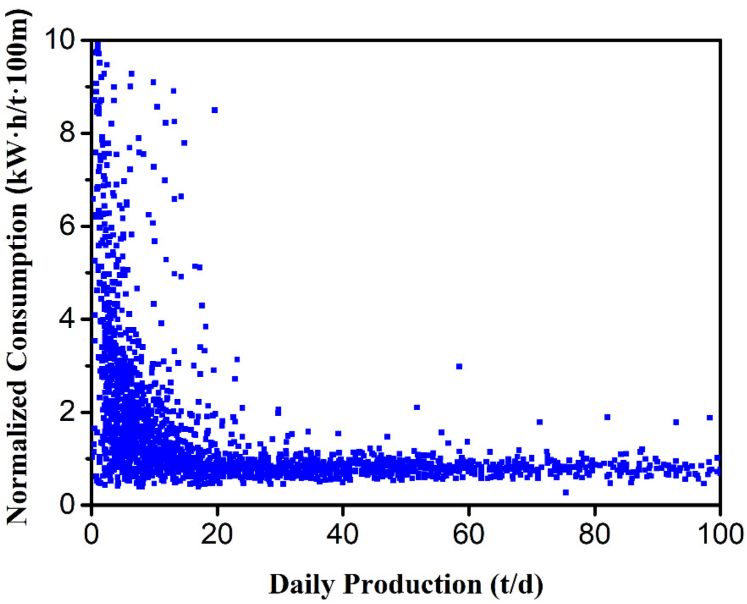

Figure 7. Impact of daily production on the normalized consumption factor for progressive cavity pump systems.

As depicted in Figure 8, the majority of pump depths for progressive cavity pump wells are less than 1200 m, significantly lower than those for the beam pump system. Furthermore, it is observed that the higher the pump depth, the lower the normalized consumption factor. For pump depths less than 600 m, the normalized consumption factor varies from 0.3 to 10 kW·h/t·100 m, whereas for depths exceeding 600 m, the normalized consumption factor for most wells is around 1 kW·h/t·100 m. There are several reasons contributing to these findings. Firstly, lower pump depths are more prone to supply shortages, resulting in lower production and consequently a decrease in the normalized consumption factor. Additionally, the two pump depth ranges represent different areas with varying well depths, suggesting that management practices in each area may also influence the results. Lastly, because the progressive cavity pump is typically used for vertical wells with low gas–oil ratios, the relationships between well angle and GOR were not discussed in this analysis.

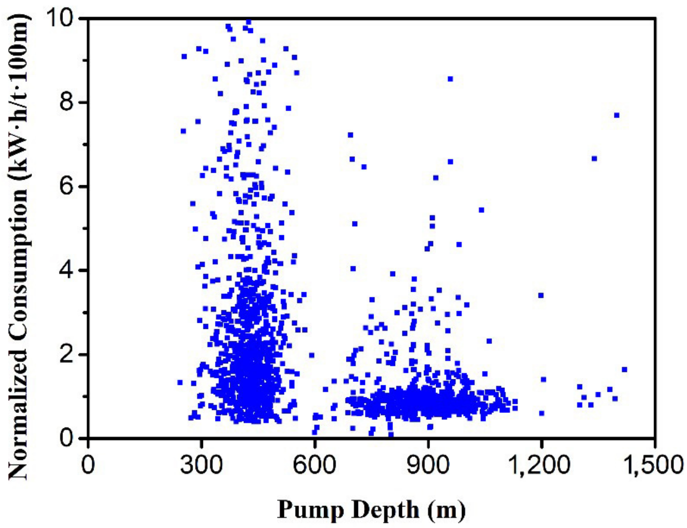

Figure 8. Impact of pump depth on the normalized consumption factor for progressive cavity pump systems.

The energy consumption of the progressive cavity pump system encompasses two main aspects. Firstly, friction is difficult to avoid, encompassing the friction between the rod and tube as well as between the rod and the liquid, particularly when dealing with high-viscosity liquids [64,65]. Moreover, inappropriate parameters such as pump or tube leakage, insufficient refill content in the pump, and inadequate clearance periods also contribute to increased energy consumption in the progressive cavity pump system. Therefore, to mitigate energy consumption, these issues must be addressed promptly. For instance, engineers should promptly adjust operating parameters, such as pump and rod types. Additionally, regular pump cleaning, particularly for wells with high viscosity, is crucial. Furthermore, timely repair of problematic wells is essential; otherwise, energy consumption may significantly increase, leading to premature equipment failure.

3.3. Electric Submersible Pump (ESP) System

ESP is typically employed in high-production wells and offshore applications. However, its small size can significantly reduce the efficiency of ESP, leading to increased energy consumption [31,66]. Due to lower production levels in the oil field, only 304 wells utilized the ESP system. Figure 9 illustrates the impact of daily production on normalized consumption factors for the ESP system. Additionally, Figure 9 indicates that production with the ESP system is significantly higher compared to pump units and progressive cavity pumps, with maximum production nearly reaching 500 t/d. The daily production of the progressive cavity pump is mainly distributed between 0–100 t/d, and most of it is concentrated between 0–20 t/d. This is mainly related to the better working efficiency, depth of application, and operational stability of the electric submersible pump. Notably, as daily production with ESP increases, the trend of the normalized consumption factor decreases, mirroring that of the beam pump system. However, the key distinction lies in the significantly lower normalized consumption factor observed in the ESP system compared to the beam pump and progressive cavity pump systems. Consequently, these comparative results affirm that the ESP system is energy-efficient.

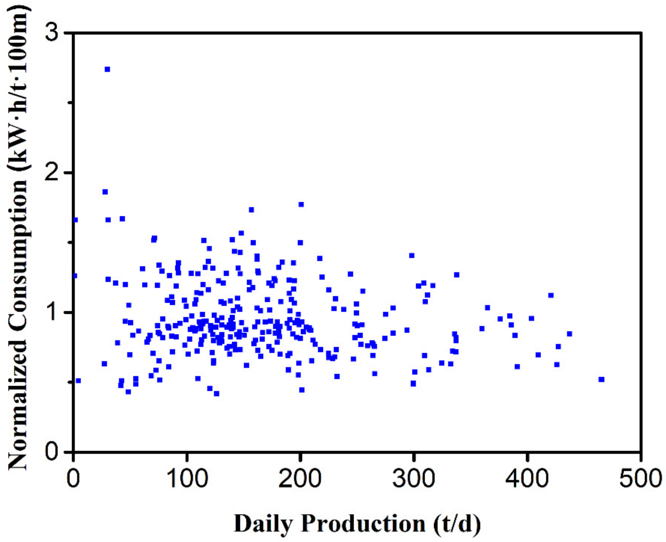

Figure 9. Impact of daily production on the normalized consumption factor for the ESP system.

As depicted in Figure 10, compared with progressive cavity pumps, electric submersible pumps are applicable to a larger depth range, mainly concentrated at about 1000 m, and a few wells can reach 2000–2500 m. The applicable depth of progressive cavity pumps is mainly below 1000 m, and a large part of it is between 300 and 600 m. This is because the electric submersible pump is driven by a motor; its applicable depth is mainly limited by the high temperature resistance of the motor and the length of the cable, depending on the performance of the motor and the cable. The progressive cavity pump, which is a type of pump that achieves liquid lifting by rotating screw motion, may not achieve the required production and efficiency in deeper wells. However, the applicable depth range of both is smaller than that of the beam pump. Notably, the normalized consumption factor for ESP is the lowest among the three production methods, with an average of around 1 kW·h/t·100 m. This is primarily attributed to its suitability for high production. ESPs are typically employed in shallow (as indicated in Figure 9) and vertical wells with no gas; hence, the relationships between daily production and well angle, as well as GOR, were not discussed here.

Although the normalized consumption factor for the ESP system is low, there are still optimization opportunities to be pursued. Energy consumption in ESP systems can be influenced by various parameters. For instance, using a pump with excessive power can result in waste, while opting for a pump with insufficient power may hinder effective field development. Additionally, energy consumption is directly related to viscosity, with higher viscosity leading to increased energy consumption. This is due to the significant increase in friction between the liquid and the components of the ESP system. Furthermore, management practices can also impact energy consumption. Therefore, in order to reduce energy consumption, it is imperative to design appropriate parameters.

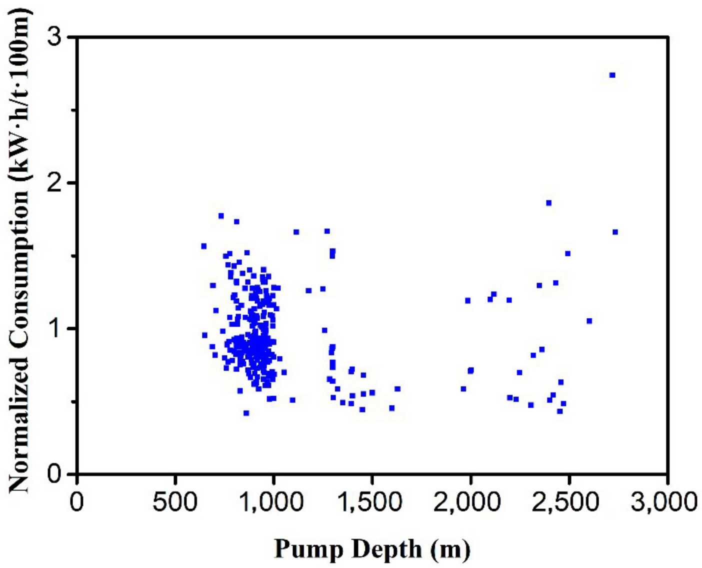

Figure 10. Impact of pump depth on the normalized consumption factor for the ESP system.

4. Conclusions

In this paper, an optimization of energy consumption in the oil field was conducted using data analysis from nearly 45,000 wells. Several conclusions were drawn:

(1) The normalized consumption factor was utilized as a metric to assess energy consumption.
(2) Higher production was found to correlate with a lower normalized consumption factor for beam pumps, progressive cavity pumps, and ESP systems.
(3) A higher gas–oil ratio (GOR) was associated with a lower normalized consumption factor for the beam pump system.
(4) The well angle was observed to have no significant relationship with the normalized consumption factor in the beam pump system.
(5) Of the 45,000 wells in the database, the wells using beam pumps account for the vast majority, followed by progressive cavity pumps, and the least frequent use is electric submersible pumps.
(6) Compared with beam pumps and progressive cavity pumps, the daily production of electric submersible pumps is the highest, between 100 and 500 t/d, while the daily production of beam pumps and progressive cavity pumps is mainly concentrated between 0 and 20 t/d.
(7) Among the three oil production systems, the well depth of the beam pump system has the largest application range, which is between 0–3500 m, followed by the electric submersible pump system, and the smallest application range of well depth is the progressive cavity pump system, mainly concentrated in the range of 300–1200 m.

Author Contributions: Conceptualization, X.L.; methodology, X.L.; validation, X.L., Z.X. and H.M.; formal analysis, X.L., Z.X. and H.M.; investigation, X.L.; resources, J.S. and G.H.; writing—original draft, X.L.; writing—review and editing, Z.X.; visualization, Z.Y.; supervision, G.H.; funding acquisition, G.H. All authors have read and agreed to the published version of the manuscript.

Funding: This work were financial support from Science Foundation of China University of Petroleum, Beijing (No. 2462023YJRC019), and National Natural Science Foundation of China (No. 52204059).

Data Availability Statement: The dataset was jointly completed by the team, so the data is not publicly available.

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

Nomenclature

C_n	the normalized consumption factor, kW·h/(t·100 m)
P_E	the useful input power, kW
P'	the effective input power, kW
T	the time, h
Q	the liquid production, t/d
H	the pump depth, m
η	the system efficiency, %

References

1. Ramos, A.J.A.; Júnior, D.S.A.; Santos, A.R.; Araújo, E.A.; Aum, P.T.P. Energy dissipation analysis of oil wells sucker rod string. *J. Braz. Soc. Mech. Sci. Eng.* **2020**, *42*, 108. [CrossRef]
2. Filho, J.C.V.H.; Schiozer, D.J. Effect of reservoir and production system integration on field production strategy selection. *Oil Gas Sci. Technol. Rev. IFP Energ. Nouv.* **2018**, *73*, 44. [CrossRef]
3. Bello, O.; Dolberg, E.P.; Teodoriu, C.; Karami, H.; Devegowdva, D. Transformation of academic teaching and research: Development of a highly automated experimental sucker rod pumping unit. *J. Pet. Sci. Eng.* **2020**, *190*, 107087. [CrossRef]
4. Cotrim, H.A.; von Hohendorff Filho, J.C.; Schiozer, D.J. Production Optimization Considering Interaction between Reservoirs and Constrained Surface Facilities. In Proceedings of the SPE Reservoir Characterisation and Simulation Conference and Exhibition, Abu Dhabi, United Arab Emirates, 9–11 October 2011; Society of Petroleum Engineers: Richardson, TX, USA. [CrossRef]
5. Garrouch, A.A.; Al-Dousari, M.M.; Al-Sarraf, Z. A pragmatic approach for optimizing gas lift operations. *J. Pet. Explor. Prod. Technol.* **2020**, *10*, 197–216. [CrossRef]
6. Shi, J.; Al-Durra, A.; Boiko, I. Optimal tracking control of artificial gas-lift process. *Comput. Chem. Eng.* **2018**, *117*, 1–10. [CrossRef]
7. Cortes, B.; Araujo, L.R.; Penido, D.R.R. Electrical submersible pump system model to assist oil lifting studies. *J. Pet. Sci. Eng.* **2019**, *174*, 1279–1289. [CrossRef]
8. Takacs, G. Sucker-Rod Pumping System Components and Their Operation. In *Sucker-Rod Pumping Handbook*; Elsevier: Amsterdam, The Netherlands, 2015; pp. 57–246. [CrossRef]
9. Uetani, T.; Furuichi, N.; Yorozu, H.; Sasaya, K.; Shibuya, T.; Kiminami, N.; Yonebayashi, H. Regaining Oil Production by Overcoming Emulsion Problems After Artificial Lift Installation. *SPE Prod. Oper.* **2018**, *33*, 300–312. [CrossRef]
10. Shi, J.; Chen, S.; Zhang, X.; Zhao, R.; Liu, Z.; Liu, M.; Zhang, N.; Sun, D. Artificial Lift Methods Optimising and Selecting Based on Big Data Analysis Technology. In Proceedings of the 11th International Petroleum Technology Conference, Beijing, China, 26–28 March 2019. [CrossRef]
11. Yu, J.; Wen, Z.; Geng, L. An Effective Experience on Reducing the Power Consumption and Produced Water Drainage of Boxi Oilfields. In Proceedings of the International Oil and Gas Conference and Exhibition in China, Beijing, China, 8–10 June 2010; Society of Petroleum Engineers: Richardson, TX, USA. [CrossRef]
12. Zhao, R.; Zhang, X.; Liu, M.; Shi, J.; Su, L.; Shan, H.; Sun, C.; Miao, G.; Wang, Y.; Shi, L.; et al. Production Optimizaton and Application of Combined Artificial-Lift Systems in Deep Oil Wells. In Proceedings of the SPE Middle East Artificial Lift Conference and Exhibition, Manama, Bahrain, 30 November–1 December 2016; Society of Petroleum Engineers: Richardson, TX, USA. [CrossRef]
13. Zhao, R.; Shi, J.; Zhang, X.; Li, J.; Peng, Y.; Xiong, C.; Liu, M.; Deng, F.; Song, S.; Miao, G. Research and Application of the Big Data Analysis Platform of Oil and Gas Production. In Proceedings of the International Petroleum Technology Conference, Beijing, China, 26–28 March 2019; Society of Petroleum Engineers: Richardson, TX, USA. [CrossRef]
14. Tian, Y.; Tian, Y.; Qu, Z.; Guo, T.; Shi, Y.; Zhang, L. A new experimental simulation method for the development of non-renewable hydrogen energy—Oil and gas resources. *Int. J. Hydrogen Energy* **2019**, *44*, 5220–5229. [CrossRef]
15. Davarpanah, A.; Mirshekari, B. A simulation study to control the oil production rate of oil-rim reservoir under different injectivity scenarios. *Energy Rep.* **2018**, *4*, 664–670. [CrossRef]
16. Davarpanah, A.; Mirshekari, B. Effect of formate fluids on the shale stabilization of shale layers. *Energy Rep.* **2019**, *5*, 987–992. [CrossRef]
17. Lei, Q.; Zhang, F.; Guan, B.; Liu, G.; Li, X.; Zhu, Z. Influence of shear on rheology of the crude oil treated by flow improver. *Energy Rep.* **2019**, *5*, 1156–1162. [CrossRef]
18. Wang, H.; Ran, Q.; Liao, X. Pressure transient responses study on the hydraulic volume fracturing vertical well in stress-sensitive tight hydrocarbon reservoirs. *Int. J. Hydrogen Energy* **2017**, *42*, 18343–18349. [CrossRef]
19. Zhang, X.; Shi, J.; Zhao, R.; Deng, F.; Li, Q.; Zhang, J.; Sun, C.; Miao, G.; Song, S. Research and Application of Overall Energy Consumption Optimization Technology Under Low Oil Price. In Proceedings of the SPE Middle East Artificial Lift Conference and Exhibition, Manama, Bahrain, 28–29 November 2018; Society of Petroleum Engineers: Richardson, TX, USA. [CrossRef]
20. Li, H.; He, J.; Misra, S. Data-Driven In-Situ Geomechanical Characterization in Shale Reservoirs. In Proceedings of the SPE Annual Technical Conference and Exhibition, Dallas, TX, USA, 24–26 September 2018; Society of Petroleum Engineers: Richardson, TX, USA. [CrossRef]
21. Li, H.; Misra, S. Assessment of miscible light-hydrocarbon-injection recovery efficiency in Bakken shale formation using wireline-log-derived indices. *Mar. Pet. Geol.* **2018**, *89*, 585–593. [CrossRef]

22. Liang, X.; Zhou, F.; Liang, T.; Su, H.; Yuan, S.; Li, Y. Impacts of pore structure and wettability on distribution of residual fossil hydrogen energy after imbibition. *Int. J. Hydrogen Energy* **2020**, *45*, 14779–14789. [CrossRef]
23. Ghareeb, M.; Shedid, S.A.; Ibrahim, M. Simulation Investigations for Enhanced Performance of Beam Pumping System for Deep High Volume Wells. In Proceedings of the International Oil Conference and Exhibition in Mexico, Veracruz, Mexico, 27–30 June 2007; Society of Petroleum Engineers: Richardson, TX, USA. [CrossRef]
24. Liu, X.; Qi, Y. A modern approach to the selection of sucker rod pumping systems in CBM wells. *J. Pet. Sci. Eng.* **2011**, *76*, 100–108. [CrossRef]
25. Xing, M.; Dong, S. A New Simulation Model for a Beam-Pumping System Applied in Energy Saving and Resource-Consumption Reduction. *SPE Prod. Oper.* **2015**, *30*, 130–140. [CrossRef]
26. Tian, Y.; Qu, Z.; Guo, T.; Tian, Y. Theoretical research on radial wells orientating hydraulically created fracture directional extended. *Int. J. Hydrogen Energy* **2017**, *42*, 18358–18363. [CrossRef]
27. Alemi, M.; Jalalifar, H.; Kamali, G.R.; Kalbasi, M. A mathematical estimation for artificial lift systems selection based on ELECTRE model. *J. Pet. Sci. Eng.* **2011**, *78*, 193–200. [CrossRef]
28. Xu, J.; Li, J.; Chen, J.; Han, M.; Han, X.; Li, J. Research on Power Saving Positive Torque and Constant Power Pumping Unit and Tracking Technique System. *Procedia Eng.* **2012**, *29*, 1034–1041. [CrossRef]
29. Zheng, D.; Miska, S.; Ozbayoglu, E.; Zhang, J. Combined Experimental and Well Log Study of Anisotropic Strength of Shale. In Proceedings of the SPE Annual Technical Conference and Exhibition, San Antonio, TX, USA, 16–18 October 2023; p. D031S046R003.
30. Garces, W.A.Z.; Rodriguez, G.M. Power Consumption Measurements & Optimization Automated with Null Electrical Risk in Esp Systems. In Proceedings of the SPE Middle East Artificial Lift Conference and Exhibition, Manama, Bahrain, 28–29 November 2018; Society of Petroleum Engineers: Richardson, TX, USA. [CrossRef]
31. Almukhtar, M.A.; Alabdulmohsin, Y.A.; Shawly, A.S.; Shehri, A.M.; Shammari, N.S.; Al-kuhlani, M. Innovative Approach to Optimize ESP Power Consumption through Developed Software. In Proceedings of the SPE Kingdom of Saudi Arabia Annual Technical Symposium and Exhibition, Dammam, Saudi Arabia, 24–27 April 2017; Society of Petroleum Engineers: Richardson, TX, USA. [CrossRef]
32. Sanchez, J.P.; Bel, O.; Festini, D. Beam Pumping System Optimization Through Automation. In Proceedings of the Latin American & Caribbean Petroleum Engineering Conference, Buenos Aires, Argentina, 15–18 April 2007; Society of Petroleum Engineers: Richardson, TX, USA. [CrossRef]
33. Shi, J.; Han, Q.; Ren, X.; Zhang, X.; Zhao, R.; Chen, S.; Li, Q.; Zheng, X. The Application of Big Data Analysis in the Optimizing and Selecting Artificial Lift Methods. In Proceedings of the SPE Middle East Artificial Lift Conference and Exhibition, Manama, Bahrain, 28–29 November 2018; Society of Petroleum Engineers: Richardson, TX, USA. [CrossRef]
34. Zheng, D.; Miska, S.; Ziaja, M.; Zhang, J. Study of anisotropic strength properties of shale. *AGH Drill. Oil Gas* **2019**, *36*, 93–112. [CrossRef]
35. Wang, F.; He, L.; Wanfu, Z.; Guochen, S.; Gang, C.; Ruiqing, C.; Deshi, Z.; Dingming, L. Application of Beam Pumping Wells's; Energy Saving Rebuilding Techniques in Daqing Oilfield. In Proceedings of the SPE Annual Technical Conference and Exhibition, New Orleans, LA, USA, 4–7 October 2009; Society of Petroleum Engineers: Richardson, TX, USA. [CrossRef]
36. Zheng, D.; Ozbayoglu, E.; Miska, S.; Zhang, J. Experimental Study of Anisotropic Strength Properties of Shale. In Proceedings of the ARMA 23241 at the 57th US Rock Mechanics/Geomechanics Symposium, Atlanta, GA, USA, 25–28 June 2023.
37. Kindi, M.; Ghadani, A.; Shekaili, S.; Aufi, F.; Al Wahaibi, S.; Gomez, C.M. Revolutionizing Oil Lift Operations: Harnessing Data Analytics for Esp Energy Management, Cost Savings, CO_2 Emissions Reduction, and Enhanced Pump Runlife. In Proceedings of the International Petroleum Technology Conference, Dhahran, Saudi Arabia, 12 February 2024. [CrossRef]
38. Denesha, D.P. Reducing Power Consumption in Rod Pumped Wells: A Digital Approach. In Proceedings of the SPE California Regional Meeting, Bakersfield, CA, USA, 27–29 March 1985; Society of Petroleum Engineers: Richardson, TX, USA. [CrossRef]
39. Kochtik, D.; Langbauer, C. Volumetric Efficiency Evaluation of Sucker-Rod-Pumping Applications Performed on a Pump Testing Facility. In Proceedings of the SPE Middle East Artificial Lift Conference and Exhibition, Manama, Bahrain, 28–29 November 2018; Society of Petroleum Engineers: Richardson, TX, USA. [CrossRef]
40. Hadzihafizovic, D. *Production Operations in Oilfield*. 2023, p. 54. Available online: https://zenodo.org/records/10338730 (accessed on 14 February 2024).
41. Wang, Y.; Wang, S.; Yang, L.; Pu, H.; Ling, K. A New Model to Evaluate Polished Rod Load of Sucker Rod Pumping System. In Proceedings of the SPE Liquids-Rich Basins Conference—North America, Midland, TX, USA, 5–6 September 2018; Society of Petroleum Engineers: Richardson, TX, USA. [CrossRef]
42. Gao, C.H.; Rajeswaran, R.T.; Nakagawa, E.Y. A Literature Review on Smart Well Technology. In Proceedings of the Production and Operations Symposium, Oklahoma City, OK, USA, 31 March–3 April 2007; Society of Petroleum Engineers: Richardson, TX, USA. [CrossRef]
43. Worth, D.; Al-Safran, E.; Choudhuri, A.; Al-Jasmi, A. Assessment of artificial lift methods for a heavy oil field in Kuwait. *J. Pet. Sci. Eng.* **2019**, *180*, 835–843. [CrossRef]
44. Valdés, J.P.; Becerra, D.; Rozo, D.; Cediel, A.; Torres, F.; Asuaje, M.; Ratkovich, N. Comparative analysis of an electrical submersible pump's performance handling viscous Newtonian and non-Newtonian fluids through experimental and CFD approaches. *J. Pet. Sci. Eng.* **2020**, *187*, 106749. [CrossRef]

45. Ricardo, D.M.M.; Jiménez, G.E.C.; Ferreira, J.V.; Meirelles, P.S. Multiphase gas-flow model of an electrical submersible pump. *Oil Gas Sci. Technol. Rev. IFP Energ. Nouv.* **2018**, *73*, 29. [CrossRef]
46. Gaspar, A.T.F.S.; Barreto, C.E.A.G.; Mazo, E.O.M.; Schiozer, D.J. Application of Assisted Optimization to Aid Oil Exploitation Strategy Selection for Offshore Fields. In Proceedings of the SPE Latin America and Caribbean Petroleum Engineering Conference, Maracaibo, Venezuela, 21–23 May 2014; Society of Petroleum Engineers: Richardson, TX, USA. [CrossRef]
47. Bai, C.; Zheng, D.; Hure, R.; Saleh, R.; Carvajal, N.; Morrison, G. The Impact of Journal Bearing Wear on an Electric Submersible Pump in Two-Phase and Three-Phase Flow. *J. Tribol.* **2019**, *141*, 051702. [CrossRef]
48. von Hollen, D.G.; Newton, S.K. Pumping Unit Optimization. In Proceedings of the SPE Latin America/Caribbean Petroleum Engineering Conference, Port of Spain, Trinidad and Tobago, 23–26 April 1996; Society of Petroleum Engineers: Richardson, TX, USA. [CrossRef]
49. Liang, X.; Zhou, F.; Liang, T. A New Intermittent Pumping Design for Fluid Shortage Wells. *Sci. Rep.* **2020**, *10*, 2559. [CrossRef] [PubMed]
50. Rafieepour, S.; Zheng, D.; Miska, S.; Ozbayoglu, E.; Takach, E. Combined Experimental and Well Log Evaluation of Anisotropic Mechanical Properties of Shales: An Application to Wellbore Stability in Bakken Formation. In Proceedings of the SPE Annual Technical Conference and Exhibition, Virtual, 26–29 October 2020.
51. Moriarty, D.G.; Renard, D.P. Proper Operation of Pumping Units Reduce Lifting Costs. In Proceedings of the SPE Production Operations Symposium, Oklahoma City, OK, USA, 27 February–1 March 1983; Society of Petroleum Engineers: Richardson, TX, USA. [CrossRef]
52. Caicedo, M.R.; Varela, S.; Beatriz, D.; Herrera, J.F. Operational Cost Saving Through Artificial Lift Optimization With Long Stroke Pumping Units in Fields of Cravo Viejo Block. In Proceedings of the SPE Artificial Lift Conference-Americas, Cartagena, Colombia, 21–22 May 2013; Society of Petroleum Engineers: Richardson, TX, USA. [CrossRef]
53. Tigrero, H.; Lainez, C.; Salinas, M. Pull & Push. Usage of the Mechanical Energy of a Conventional Sucker Rod Lift in Shallow Wells. In Proceedings of the SPE Latin American and Caribbean Petroleum Engineering Conference, Quito, Ecuador, 18–20 November 2015; Society of Petroleum Engineers: Richardson, TX, USA. [CrossRef]
54. Zheng, D.; Turhan, C.; Wang, N.; Ashok, P.; van Oort, E. Prioritizing Wells for Repurposing or Permanent Abandonment Based on Generalized Well Integrity Risk Analysis. In Proceedings of the SPE/IADC Drilling Conference and Exhibition, Galveston, TX, USA, 5–7 March 2024; p. D021S018R001.
55. Byrd, J.P.; Beasley, H.L. Predicting Prime Mover Requirements, Power Costs, and Electrical Demand for Beam Pumping Units. In Proceedings of the Annual Technical Meeting, Calgary, Alberta, 6–9 May 1974; Society of Petroleum Engineers: Richardson, TX, USA. [CrossRef]
56. Skinner, D.R. Efficient Use of Electric Power in Production Operations. *J. Pet. Technol.* **1984**, *36*, 1326–1334. [CrossRef]
57. Zheng, D. Geological Analysis and Cement Composition for Improving Zonal Isolation. Ph.D. Thesis, The University of Tulsa, Tulsa, OK, USA, 2023.
58. Brandt, J.U.; Lewerenz, J.; Mueller-Link, D.; Reichwage, M. Development of a Multiphase Down-hole Twin-screw Pump and its Use in Multiphase-operated Transport Networks. *Oil Gas Eur. Mag.* **2015**, *41*, 153–156.
59. Zheng, D.; Ozbayoglu, E.; Miska, S.; Liu, Y. Cement Sheath Fatigue Failure Prediction by ANN-Based Model. In Proceedings of the Offshore Technology Conference, Houston, TX, USA, 2–5 May 2022. [CrossRef]
60. Zheng, D.; Miska, S.; Ozbayoglu, E. The Influence of Formation Creeping on Wellbore Integrity. In Proceedings of the SPE 2021 Symposium Compilation, Virtual, 26 November 2021.
61. Zheng, D.; Miska, S.; Ozbayoglu, E.; Zhang, Y. The Influence of Elliptical-Geometry Wellbore on Zonal Isolation. In Proceedings of the 56th U.S. Rock Mechanics/Geomechanics Symposium, Santa Fe, NM, USA, 26–29 June 2022.
62. Zheng, D.; Ozbayoglu, E.; Miska, S.; Liu, Y. Cement Sheath Fatigue Failure Prediction by Support Vector Machine Based Model. In Proceedings of the SPE Eastern Regional Meeting, Wheeling, WV, USA, 18–20 October 2022.
63. Zheng, D.; Ozbayoglu, E.; Baldino, S.; Miska, S.; Liu, Y. The Influence of Casing Eccentricity on Zonal Isolation. In Proceedings of the ARMA 23241 at the 57th US Rock Mechanics/Geomechanics Symposium, Atlanta, GA, USA, 25–28 June 2023.
64. Mueller-Link, D.; Rohlfing, G.; Spelter, H. Twin-Screw Pumps Help Improving Oil Recovery in Mature Fields and Transfer Heavy Crude Oil over Long Distances. *Oil Gas Eur. Mag.* **2009**, *35*, 127–131.
65. Guo, S.; Zheng, D.; Chen, T. Controlling the hydration rate of alkali-activated slag by the slow release of NaOH. *Geoenergy Sci. Eng.* **2023**, *228*, 211960. [CrossRef]
66. Mazzola, R.; Colla, M.; Teodoulou, M.; Ballarini, M.; Pereyra, M.; Muñoz, H.; Bruni, M.; Teves, R.; Oyarzun, R. Study To Improve Energy Efficiency Using ESP. In Proceedings of the SPE Artificial Lift Conference—Latin America and Caribbean, Salvador, Bahia, Brazil, 27–28 May 2015; Society of Petroleum Engineers: Richardson, TX, USA. [CrossRef]