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A brief overview of advanced drilling methods in petroleum and natural gas engineering

Petrol ve doğal gaz mühendisliğinde ileri düzey sondaj yöntemlerine dair kısa bir genel değerlendirme

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Abstract

Advanced drilling technologies like horizontal directional drilling, multilateral drilling, extended reach drilling, and directional drilling have greatly improved oil and gas extraction efficiency, especially in challenging reservoirs. These methods access previously unreachable reserves, optimize reservoir drainage, and boost production rates. Multilateral wells are ideal for low-permeability reservoirs, and extended reach drilling has transformed offshore exploration by reducing platform costs. The integration of electrified systems and real-time monitoring will further enhance precision, minimize risks, and improve well management. Innovations like wireless downhole communication and inductive coupling will enable better control and monitoring. With a focus on sustainability, these technologies will reduce environmental impacts and operational costs. Ongoing research will address fluid management, coning control, and reservoir optimization, making multilateral wells a cost-effective solution for enhanced oil recovery and assisted gravity drainage. These evolving technologies promise a more efficient and sustainable future for oil and gas exploration

Keywords: Horizontal directional drilling; Multilateral drilling; Extended reach drilling; Directional drilling; Enhanced oil recovery

Öz

Yatay yönlü sondaj, çok kollu sondaj, uzatılmış erişimli sondaj ve yönlendirilmiş sondaj gibi ileri düzey sondaj teknolojileri, özellikle zorlu rezervuarlarda petrol ve doğalgaz üretim verimliliğini önemli ölçüde artırmıştır. Bu yöntemler, daha önce erişilemeyen rezervuarların üretime açılmasını sağlamakta, rezervuar drenajını optimize etmekte ve üretim oranlarını artırmaktadır. Çok kollu kuyular, düşük geçirgenlikli rezervuarlar için ideal bir çözüm sunarken, uzatılmış erişimli sondaj, açık deniz aramalarında platform maliyetlerini azaltarak önemli bir dönüşüm yaratmıştır. Elektrikli sistemlerin entegrasyonu ve gerçek zamanlı izleme uygulamaları, hassasiyeti artıracak, riskleri en aza indirecek ve kuyu yönetimini iyileştirecektir. Kablosuz kuyu içi iletişim ve endüktif bağlantı gibi yenilikler ise kontrol ve izleme kapasitesini daha da geliştirecektir. Sürdürülebilirliğe odaklanan bu teknolojiler, çevresel etkileri ve operasyonel maliyetleri azaltacaktır. Devam eden araştırmalar; akışkan yönetimi, konikleşme kontrolü ve rezervuar optimizasyonu gibi konulara çözüm sunarak, çok kollu kuyuları gelişmiş petrol geri kazanımı ve destekli yerçekimi drenajı için maliyet etkin bir seçenek haline getirecektir. Bu gelişen teknolojiler, petrol ve gaz aramacılığında daha verimli ve sürdürülebilir bir geleceğin yolunu açmaktadır..

Anahtar kelimeler: Yatay yönlü sondaj, Çok kollu sondaj; Uzatılmış erişimli sondaj; Yönlü sondaj; Gelişmiş petrol Geri kazanımı

1 Introduction

The formation of oil and natural gas, along with the exploration of their properties, is crucial for understanding the broader energy landscape. This includes investigating the origins of oil, its migration through geological layers, the formation of oil and gas reservoirs, and key geological elements such as underground mapping, source rocks, and the seals that trap petroleum [1, 2]. Additionally, understanding the migration of oil and natural gas, the creation of traps, and exploration techniques used in petroleum geology is vital for locating and producing these valuable resources [3, 4]. Natural gas, in particular, forms through distinct processes and exhibits unique underground behaviours, which are essential for predicting its future potential. Given global energy demands, oil and natural gas reserves are likely to remain the dominant energy sources for the foreseeable future unless reliable and scalable alternative energy sources emerge [5, 6].

Since its inception, the oil and gas industry, particularly the exploration and production sectors, has undergone significant transformations, most notably in drilling technologies and well completion techniques. Early wells were relatively shallow, vertical, and deviating from a straight path was undesirable due to the limitations of early drilling technology and insufficient engineering knowledge [7, 8]. The primary goal was to drill a vertical well to a predetermined depth directly beneath the wellhead.

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However, as the demand for energy grew and the need to discover new reserves increased, companies began drilling deeper and exploring more challenging environments, such as deep-sea locations, densely populated areas, and ecologically sensitive regions. This shift sparked a major evolution in drilling technology, with new methods and tools developed to economically and efficiently exploit these deeper and more remote reserves [9].

Today, drilling costs can easily exceed millions of dollars per well, highlighting the importance of well completion design to optimize production. Initially, vertical drilling was the norm, with the focus on simply reaching a specific depth without much concern for precise underground locations [10]. As drilling challenges grew, directional drilling emerged, enabling more complex and precise well trajectories that allowed exploration of previously inaccessible reserves. Modern drilling techniques aim to maintain a controlled path and reach the desired depth while navigating complex geological formations. Wells can be drilled vertically or directionally, though maintaining true verticality can be challenging [11, 12]. As the length of the drill pipe increases, gravity causes bending and potential deviation from the intended path. In some cases, this deviation is acceptable; in others, it can lead to costly setbacks [13]. Directional drilling involves steering the wellbore along a predetermined path to reach a target zone, often in collaboration with drilling service providers to meet strategic exploration goals. Successfully planning a directional well requires a thorough understanding of the well's purpose and the target zone's underground coordinates [14].

Vertical drilling remains the traditional method, where the wellbore is divided into three sections of varying diameters, from the surface to the final depth. The first section is the largest, followed by narrower sections in subsequent stages [15, 16]. Horizontal drilling, while similar to directional drilling, is another vital technique. In this method, the wellbore is initially vertical, but once it reaches a certain depth, it is gradually redirected to run parallel to the oil-bearing zone. The angle required for the well to be considered "horizontal" does not necessarily need to be 90 degrees [17]. Specialized equipment such as downhole motors or rotary steerable systems (RSS) allows for precise control of the drill bit's direction [18]. Directional drilling encompasses various well paths, including horizontal, all designed to access specific target zones underground. A key feature of these systems is their ability to adjust the wellbore's trajectory during drilling, unlike traditional vertical drilling systems [19]. However, challenges can arise when subsurface conditions, such as changes in stratigraphy or variations in weight-on-bit, cause deviations from the planned path. The weight-on-bit significantly impacts the rate of penetration (ROP), making its optimization crucial for efficient drilling [20].

This study presents a comprehensive examination of the evolution and technical development of drilling methods in the oil and gas industry, with a particular emphasis on the transition from conventional vertical drilling to more advanced approaches such as horizontal and directional drilling. By analysing these technological advancements, the study aims to explain the transformative changes within the industry and assess their implications for future exploration and production strategies. In addition, the article identifies persistent limitations in directional control and real-time adaptability in complex geological formations, and it proposes integrated engineering solutions to address these challenges effectively.

2 Material and methods

The methodology adopted in this study is primarily descriptive and explanatory in nature. It provides a detailed account of the evolution of drilling techniques in the oil and gas industry, with a particular emphasis on the transition from traditional vertical drilling to advanced directional and horizontal drilling methods. To ensure analytical depth, the study incorporates selected case examples from both onshore and offshore drilling operations, focusing on industry-reported developments and peer-reviewed literature. Data sources include technical reports from major oilfield service companies, governmental energy agencies, and scholarly databases such as Science Direct and Web of Science. Criteria for selecting examples were based on their relevance to illustrating technological milestones, complexity of geological settings, and the practical implications for drilling efficiency and cost reduction. In analysing these cases, particular attention was paid to technical parameters such as wellbore trajectory control, weight-on-bit optimization, and rate of penetration. This approach allows for a structured comparison of drilling techniques and helps assess how these innovations have enhanced resource accessibility and operational safety across different geological conditions.

3 Horizontal directional drilling

Horizontal wells, drilled at near-horizontal angles, have gained practical significance with advancements in solid-state electronics enabling precise directional drilling. Their primary objectives include maximizing contact with hydrocarbon-bearing fractures especially in limestone and shale formations minimizing water or gas coning in thin oil zones, and enhancing both drainage area and wellbore surface to boost recovery, particularly in heavy oil reservoirs. Additionally, they facilitate efficient access to steeply dipping layered reservoirs, improve coalbed methane extraction, and optimize the injection of various fluids such as water, gas, steam, or chemicals into the reservoir. An alternative to horizontal drilling is vertical drilling combined with hydraulic fracturing. However, this approach seldom achieves the objectives of horizontal wells, as hydraulic fractures often fail to intersect multiple natural fractures and may inadvertently connect to underlying water zones. Moreover, proppant-filled fractures do not function effectively as drainage paths [21]. Originating in the oil and gas industry, horizontal directional drilling is a trenchless technique used to install underground pipelines with minimal environmental disruption and without damaging surface infrastructure. The process begins with drilling a pilot hole at an 8-16° entry angle, which is then enlarged using reamers before inserting the product pipe (Figure 1). High-performance drilling fluids are employed to transport cuttings, stabilize the borehole, and cool the drill bit [22]. In deviated and horizontal drilling, *torque (T)* and *drag (D)* arise primarily from friction against the wellbore. The soft-string (cable) model yields (Equation 1) [23].

$$\frac{dF}{ds} = \mu N(s), \frac{dT}{ds} = \tau(s) \qquad (1)$$

where:
F and T are axial and torsional forces along the drill string,
s is the wellbore arc length,
μ is the drilling fluid friction coefficient,
N(s) is the normal contact force,
τ(s) represents torsional resistance.

The dynamic transport of solid particles through inclined wellbores follows two-phase flow models. Bed height h_c can be expressed as (Equation 2).

$$h_c = f(V_a, \tau_y, \emptyset, \beta) \qquad (2)$$

where:
V_a is the annular velocity,
τ_y is the fluid yield point,
$\emptyset$ is particle volumetric fraction,
β is the wellbore inclination.

Coning occurs when reservoir fluid is drawn into the wellbore, governed by a critical drawdown. A commonly used correlation is the Craft–Hawkins model (Equation 3).

$$q_{critical} = C.b'\sqrt{k_r h \Delta_\rho} \qquad (3)$$

where:
C is an empirical constant,
b'=hp/h is the normalized perforated interval,
k_r is reservoir permeability,
h is total formation thickness,
Δ_ρ is density difference between fluids.

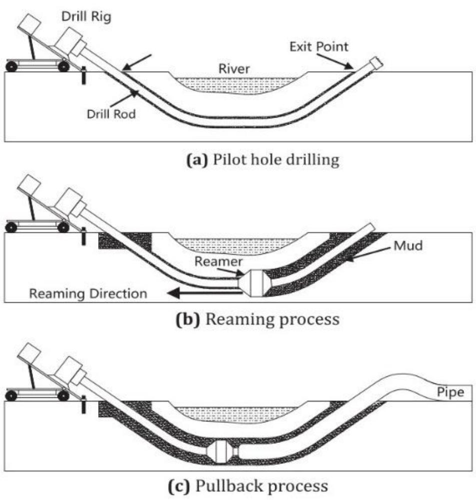

Figure 1. Horizontal directional drillings method [22].

4 Multilateral drilling method

The concept of multilateral wells (ML) emerged in the 1950s when Russian engineers introduced this innovative technique as a significant advancement in drilling technology. Since then, multilateral well technology has rapidly developed and gained international recognition. In 1995, Phillips Petroleum achieved a key milestone by completing the first trilateral well in the North Sea, showcasing the potential of this new approach. The following year, Norsk Hydro advanced the technology further by successfully completing the first Level 5 ML in the Oseberg Field, also in the North Sea. In 1998, Shell took another major step by completing the first Level 6 ML in California [24, 25]. Table 1 summurizes technology advancement of multilateral laterals (TAML) levels for multileteral well construction. A multilateral well consists of multiple lateral branches that extend from a single main bore, optimizing oil and gas production by providing access to a larger portion of the reservoir. This technology is particularly beneficial in reservoirs with low permeability, such as shale oil, tight oil, and offshore wells [26]. Even before the widespread use of horizontal drilling, multilaterals were recognized as an effective method to access extensive reservoir areas, offering a more efficient way to exploit challenging deposits. By increasing the drainage area, multilateral wells significantly boost production and reduce operational costs through the drilling of multiple lateral wells [27]. Although drilling multilateral wells typically incurs higher costs than conventional vertical wells, the increase in oil production and recovery factor far outweigh the initial expense.

Table 1. TAML levels for multilateral well construction

TAML Level	Description	Key Characteristics
Level 1	Bare open hole lateral	No junction support; uncontrolled re-entry; minimal complexity
Level 2	Cased and cemented main bore with open hole lateral	Minimal mechanical support; limited re-entry capability
Level 3	Mechanical support at junction in open hole lateral	Improved access; mechanical stability at junction
Level 4	Lateral and main bore both cased, with non-sealing junction	Mechanical isolation; selective intervention possible
Level 5	Pressure-isolated junction with full re-entry capability	Hydraulic isolation; active flow control; enhanced operational flexibility
Level 6	Fully sealed and cemented junction with high integrity	Complete pressure isolation; integrity suited for complex reservoir environments

This enhancement in production can be attributed to the increased contact area between the well and the reservoir. In situations where rig size is limited but a deep well with a large contact area is required, multilateral wells offer a practical and highly effective solution [28]. Multilateral wells unlock significant production potential in reservoirs of various sizes by extending multiple laterals from the main borehole. This extension increases the contact area with the reservoir, improving sweep volume and overall reservoir drainage. Additionally, multilateral wells are more cost-effective and environmentally friendly compared to drilling separate wells. However, the construction and completion of these wells present substantial challenges. There is minimal margin for error during directional drilling, and the completion process requires significant investment in advanced technologies for remote monitoring of production. Therefore, ongoing research and development in multilateral technologies are essential to overcoming these challenges and ensuring their broader adoption within the industry [29]. The implementation of multilateral well completions has experienced significant growth in recent years, largely driven by advancements in directional drilling and well completion technologies. One of the main advantages of multilateral wells is their ability to address challenges such as coning, where the influx of water or gas from underlying reservoirs negatively impacts oil production. In reservoirs with an underlying aquifer or gas cap, multilateral wells mitigate the detrimental effects of coning by enabling more efficient control over the flow of fluids. This ability to manage fluid influx significantly reduces both initial investments and ongoing operational costs, making it a highly cost-effective solution. Moreover, when integrated with enhanced oil recovery (EOR) techniques or assisted gravity drainage (AGD), multilateral wells can boost oil production while maintaining a more economical approach. These wells facilitate increased production rates by optimizing reservoir drainage and improving overall recovery efficiency. Over the past few decades, continuous advancements in drilling tools and technologies have allowed engineers to refine multilateral well designs, providing the flexibility to adapt to various reservoir conditions and operational needs (Figure 2). These innovations have led to the development of multiple design strategies, further enhancing the versatility and performance of multilateral well completions. As a result, multilateral well technology has become a crucial tool in modern oil and gas production, particularly for reservoirs that require a more sophisticated and efficient approach to maximize production while effectively managing costs.

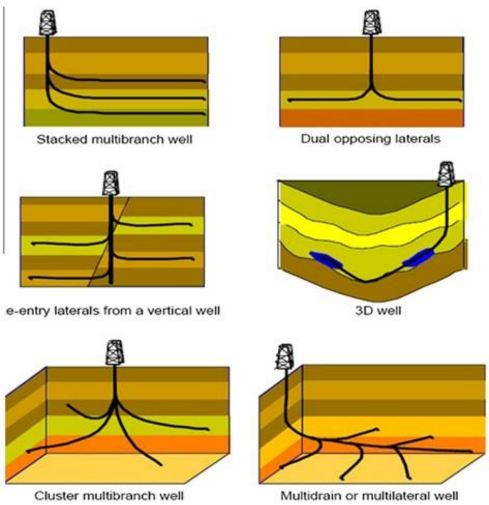

Figure 2. Different categories of advanced well designs [28].

The transition toward electrically controlled systems in both conventional and multilateral wells is expected to accelerate in the near future, as hydraulic control systems are increasingly seen as insufficient to meet the growing demands of modern oil and gas production. Electrically controlled systems offer greater precision, reliability, and flexibility in managing well operations, especially in achieving full flow control within the well. Table 2 compare response time and power delivery between electric and conventional electro-hydraulic downhole control systems. By allowing more precise regulation of fluid flow, these systems enable detailed formation analysis without relying on traditional well shut-in tests, which can be time-consuming and costly. The increasing demand for enhanced real-time well monitoring and better control across both the main bore and lateral sections of the reservoir has driven significant advancements in sensing and communication technologies. As operators seek to optimize production and ensure safety, there is growing demand for systems that provide continuous, accurate data on well conditions and reservoir behavior. Innovations such as wireless downhole communication, inductive coupling for electrical transmission, and downhole power generation and storage systems for operating flow control valves and sensor arrays are at various stages of development. These innovations have the potential to revolutionize multilateral well operations by enabling real-time control and monitoring across all wellbore sections (Figure 3). The implementation of these advanced technologies will lead to more efficient, cost-effective, and sustainable production from multilateral wells, ultimately enhancing recovery rates and reducing operational risks. As these systems become increasingly reliable and economically viable, they will play a pivotal role in the future of well completion and management, particularly in complex reservoirs where precision and adaptability are crucial for maximizing production potential. Significant technological gaps persist in the development of power solutions for downhole sensors aimed at enabling autonomous and permanent monitoring. Overcoming these challenges necessitates advancements in thermally robust energy storage systems, energy-efficient communication protocols, and low-power signal processing architectures. Downhole monitoring technologies are predominantly constrained by power availability and the severity of environmental conditions. Specifically, battery longevity is severely limited under high-pressure, high-temperature conditions, thereby restricting sustained autonomous operation. Moreover, the substantial power consumption associated with wireless data transmission restricts achievable data rates and monitoring frequency. The demanding downhole environment requires ruggedized sensor components, which in turn elevate energy demands for environmental compensation. Furthermore, the computational requirements for on-board data processing essential for data compression and real-time analytics further exacerbate the power budget constraints.

Table 2. Electric vs. electro-hydraulic downhole controls.

Criterion	Electro-Hydraulic Systems	All-Electric Systems
Valve Actuation Time	Typically 20–25 s per step, as observed in electro-hydraulic multizone systems	Shorter reaction times achieved via high-torque electrical motors, reducing cycle time significantly compared to hydraulic units
Power Delivery	Requires hydraulic power units at surface; susceptible to leakage; limited transmission lines	High-voltage downhole electric lines/umbilicals enable efficient power delivery and bidirectional telemetry, no hydraulic piping required
System Complexity	Multiple hydraulic lines, higher leak risk, substantial surface footprint	Single electric line with contactless wet-mate connectors simplifies installation and enhances reliability
Operational Benefits	Reliable actuation, but limited zone count due to hydraulic line complexity	Real-time zone-level control, continuous monitoring, extended step-outs, and improved recovery efficiency

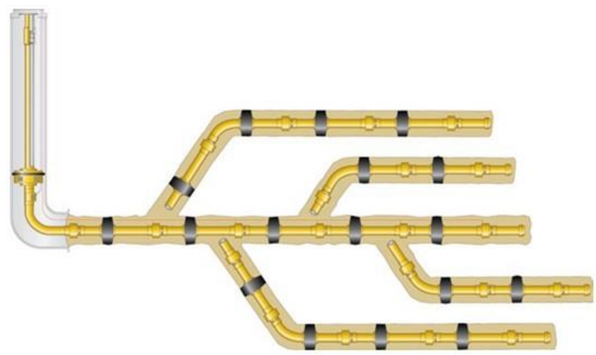

Figure 3. A sophisticated multilateral well integrating wireless communication technology [27].

5 Extended reach drilling method

Extended reach drilling (ERD) has garnered significant attention since its first major successful application in 1993, rapidly becoming a widely adopted technique in oil and gas exploration [30]. ERD involves drilling directional or horizontal wells with a horizontal displacement (HD) exceeding 3,000 meters and a ratio of HD to true vertical depth greater than 2.0. The current record for the longest ERD well stands at an impressive 15,000 meters, with a horizontal displacement of 14,129 meters. This breakthrough has revolutionized the approach to accessing oil and gas reservoirs, particularly in challenging locations. In offshore environments, large-scale cluster extended reach wells (ERWs) are drilled from a single offshore platform, as shown in Figure 4 [31]. This approach has proven highly effective for addressing challenges related to utilizing sea areas, expanding the platform's operational range, and significantly reducing the costs associated with oil and gas development. By drilling multiple extended reach wells from a single platform, companies can access oil and gas reserves that would otherwise be difficult or uneconomical to reach.

Today, various well construction methods are used to develop oil and gas reservoirs, even within the same field. The selection of the most appropriate method depends on factors such as the reservoir's depth, type, local lithology, proven reserves, anticipated drilling challenges, and cost considerations [32]. Extended reach drilling stands out as a technology that enables the drilling of longer horizontal wells at higher inclination angles. This capability is essential when exploring underground oil or natural gas deposits located far from the drilling site, particularly when drilling directly above the deposit is not feasible. In traditional vertical drilling, wells are drilled directly downward to access subsurface deposits. However, when these deposits lie beneath obstacles such as mountains, rivers, or densely populated areas, vertical drilling becomes challenging. ERD, as an advanced form of directional drilling, allows for wells to be drilled from nearby surface locations, using high inclination angles to reach deposits that would otherwise remain inaccessible [33]. By increasing the inclination angle and drilling horizontal wells over greater distances, ERD enables the exploration of reserves located farther from the drilling rig, making it an invaluable technique in modern oil and gas exploration [34].

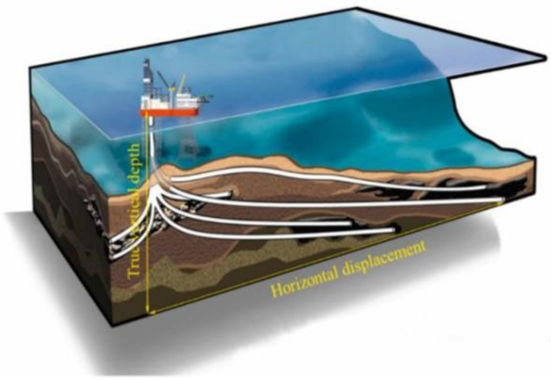

Figure 4. Offshore large-scale cluster ERWs [31].

In contrast to vertical wells, directional and extended-reach wells are divided into three distinct cleaning zones based on the hole's inclination angle: the I zone (0-30°), the II zone (30-60°), and the III zone (60-90°) (Figure 5) [34]. As the borehole deviation exceeds 10°, cuttings tend to accumulate on the lower walls of the wellbore, and this accumulation becomes more pronounced as the inclination increases. In practice, the most significant build-up of cuttings typically occurs in the third zone, where the inclination ranges between 30° and 60°. Empirical studies corroborate that cuttings accumulation within Zone II (30°-60°) is highly sensitive to annular velocity and fluid rheology particularly the yield point. Xu et al. [35] demonstrated a direct dependency of bed height on these parameters, especially under inclined conditions. Muds with intermediate rheology (PV = 14, YP = 14) yield thinner beds and that bed sliding occurs predominantly between 35° and 55°[36]. Similarly, Tomren et al. [37] identified 40°-50° as a critical range where cuttings deposition intensifies, and Sifferman and Becker [38] confirmed that annular velocity and yield point are the dominant factors in controlling bed height at these inclinations. The hole cleaning process involves the interaction between cuttings and the mud column. Cuttings experience both upward positive forces and downward negative forces. Depending on the type of mud used, cuttings either fall or slide through stationary parts of the mud column. In lower viscosity mud, cuttings descend more quickly, whereas in more viscous mud, they move more slowly. To efficiently remove the cuttings from the bottom of the well and bring them to the surface, the annular mud velocity must exceed the rate at which the cuttings slide downward through the mud column. This ensures that the cuttings are lifted and carried upward by the circulating mud flow, effectively clearing the wellbore and preventing blockages or damage to drilling equipment. Proper hole cleaning is essential to maintaining drilling efficiency, especially in directional and extended-reach wells, where the challenges of cuttings removal are more complex due to the increased wellbore inclination.

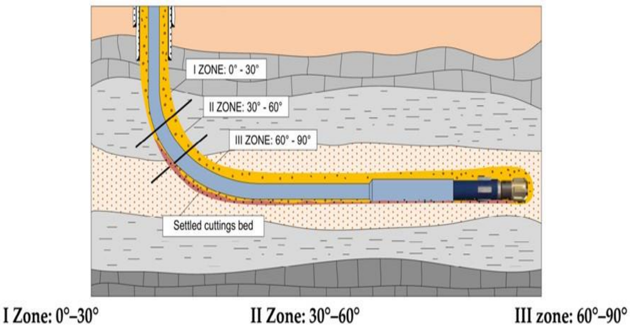

Figure 5. Cleaning zones in extended-reach wells [34].

In recent years, extended reach drilling technology has been increasingly adopted in energy and petroleum projects, offering innovative solutions for accessing hard-to-reach deposits. One significant application of ERD is its ability to drill horizontal wells from land to reach and produce oil or natural gas from beneath the seabed. This eliminates the need to construct offshore platforms directly above the deposits and drill vertical wells, enhancing both cost-effectiveness and production efficiency from complex offshore reservoirs. ERD technology has also seen successful application in Japan, where Japan Petroleum Exploration Co., Ltd. (JAPEX) has gained extensive experience in drilling both horizontal and vertical extended reach wells. In 2014, JAPEX achieved a major milestone by drilling a horizontal well at the Yufutsu oil and gas field in Tomakomai City, Hokkaido, with a total depth of 4,600 meters and a horizontal length of 500 meters. This accomplishment marked a significant advancement in accessing previously challenging oil and gas reserves. Additionally, in alignment with Japan's carbon dioxide capture and storage (CCS) efforts, JAPEX has utilized ERD technology to support environmental initiatives. Specifically, as part of the CCS demonstration project offshore Tomakomai, led by Japan CCS Co., Ltd. (JCCS), JAPEX completed the drilling of CO_2 injection wells for feasibility studies. In 2015, JAPEX achieved another milestone by completing the longest extended reach well in Japan, with a deviation of 4,346 meters, a total drilling length of 5,800 meters, and a vertical depth of 2,753 meters. The deviation of this well was equivalent to seven times the height of the Tokyo Skytree, demonstrating ERD technology's ability to overcome significant technical challenges [39]. The flow configuration of the Tomakomai CCS project, shown in Figure 6, involves CO_2 sourced from the pressure swing adsorption offgas of a hydrogen production unit at an oil refinery along the Tomakomai Port coastline. The CO_2-rich offgas is transferred to the Tomakomai demonstration project's CO_2 capture facility via a 1.4 km pipeline. In the capture facility, CO_2 is extracted from the offgas using a commercially established amine scrubbing process, with a capacity to handle up to 200,000 tonnes per year, ensuring a high purity CO_2 (99% or greater) for storage or further use [40].

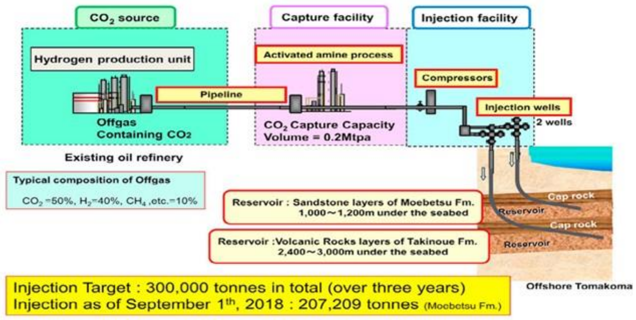

Figure 6. flow configuration of the Tomakomai Project [40].

6 Directional drilling method

Horizontal wells are crucial in industries such as oil and gas, particularly in regions like Canada, where they play a key role in extracting heavy oil from deep reservoirs. A horizontal well is typically drilled through a curved section of the wellbore, where the angle gradually increases to 90 degrees. Once this angle is achieved, the wellbore maintains this inclination over a considerable length to maximize exposure to the reservoir, which significantly enhances oil recovery [41]. Based on the curvature and length of the horizontal section, horizontal wells are classified into medium, short, and long radius categories. The selection of the appropriate category depends on specific geological and engineering requirements, ensuring optimal well design and production efficiency [17]. Directional drilling, a key method for altering the wellbore's angle during drilling, is used to steer the well to the desired target location. Once the well reaches a certain depth, its direction is deliberately changed, with two common types of directional wells: J-type and S-type (Figure 7). The J-type well is deviated at a predetermined depth to a planned slope and is maintained at this angle until the target depth is reached. This is the most widely used method due to its simplicity and straightforward design. On the other hand, S-type wells are also deviated initially but become more vertical or nearly vertical as they near the target. This design is particularly useful when bypassing certain geological formations or challenges along the wellbore path is necessary [42, 43]. Directional drilling requires specialized equipment and techniques to precisely alter the wellbore's path. Downhole measurements are crucial in monitoring the well's orientation and trajectory, providing real-time feedback to ensure the well reaches the desired location and angle. Careful planning and execution are vital to ensure the well performs optimally and avoids complications from problematic formations. In cases of difficult-to-drill formations, the wellbore may need to be cased off to mitigate potential issues. Deviation control is a crucial aspect of directional drilling, encompassing all the steps necessary to ensure the well is drilled according to the planned path and geological data. Since its introduction, directional drilling has become widely adopted in the oil and gas industry. Technological advancements have significantly improved the ability to design and execute complex well profiles with greater flexibility and precision, providing solutions for more challenging and unconventional reservoirs [44].

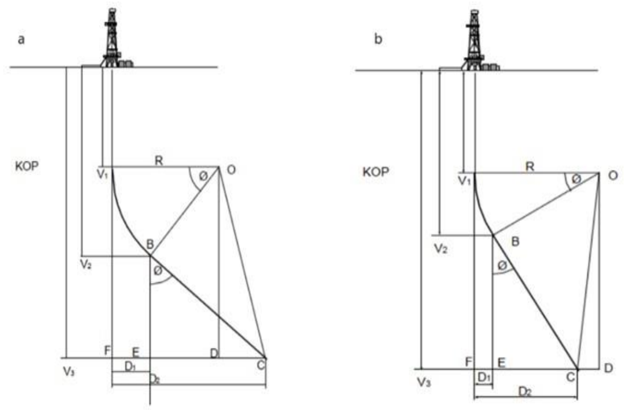

Figure 7. Types of Directional Drilling a) a J-Type Well, R<D; b) a J-Type Well, R>D [42].

Directional drilling involves several key terminologies that are essential for understanding the direction, trajectory, and design of a wellbore. One of the primary concepts is inclination, which refers to the angle between the vertical line extending from the surface location of the drilling rig and the tangent line at a specific point within the wellbore. This angle, typically expressed in degrees, indicates how much the wellbore deviates from the vertical axis. Inclination is often measured using advanced tools such as measurement-while-drilling accelerometers and gyroscopes, which provide real-time data on the wellbore's angle during the drilling process. Another critical term is azimuth, which denotes the angle between the vertical projection of the well on a horizontal plane and true north (or magnetic north). Measured clockwise from north, azimuth helps define the horizontal direction in which the wellbore is being drilled, allowing engineers and drillers to assess its orientation relative to geographic directions (Figure 8) [45]. Together, inclination and azimuth provide a comprehensive understanding of the well's orientation and trajectory. These measurements are crucial for guiding the drilling process, enabling engineers to make real-time adjustments to ensure the well remains on the intended path. By closely monitoring these parameters, potential obstacles can be avoided, geological challenges navigated, and unintended deviations from the desired wellbore path prevented [44, 46].

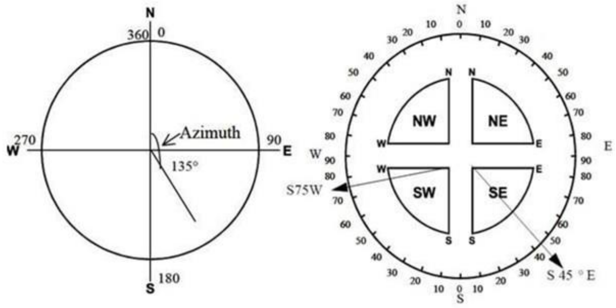

Figure 8. Azimuth direction [45].

The advancement of directional drilling techniques is primarily driven by the continuous development of sophisticated tools and technologies, as illustrated in Figure 9 [19]. These innovations have progressed from basic real-time monitoring systems to more advanced capabilities such as digitized visualization, automation, integration, and intelligence. These cutting-edge tools enable engineers to monitor, adjust, and optimize the drilling process in real time, significantly improving both efficiency and precision. However, the challenges faced in directional drilling are distinct from those encountered in traditional vertical deep drilling. One of the most critical challenges, especially in highly deviated and horizontal wells, is cuttings transport. In such wells, gravity settling can cause cuttings to accumulate on the lower portion of the wellbore, making it difficult to remove them effectively. The design of the well path is crucial in overcoming this issue. A well-designed path reduces the complexities associated with deviated and horizontal wells by ensuring that cuttings can be efficiently transported to the surface, thus maintaining wellbore cleanliness and minimizing the risk of stuck pipe incidents. Another significant challenge is the high torque and drag exerted on the drill string, particularly when it rests on the lower section of the wellbore. These forces can lead to equipment failure and slow down drilling progress. Therefore, carefully designing the well path to minimize torque and drag is essential. Factors such as mud lubricity, well path geometry, and drill-string buckling can exacerbate these challenges. To mitigate these issues, high-quality drilling fluids with good suspension capability and lubricity are essential. These fluids help reduce friction and manage drag, improving the overall efficiency of the drilling process. Additionally, wellbore stability remains a critical concern in directional drilling. Unstable wellbore conditions can complicate casing and liner running operations, while casing wear can become a significant issue, especially when rotary drilling techniques are employed to minimize drag. Proper management of these challenges is vital to ensure the integrity of the well and maintain operational efficiency throughout the drilling process. Finally, measurement while drilling technology plays an indispensable role in ensuring accurate target penetration. Measurement while drilling provides real-time data on the well's position and trajectory, allowing drillers to make immediate adjustments to ensure the well remains on course and reaches the intended target depth. The combination of these advanced tools, optimal well path design, and effective management of challenges such as drag, torque, and wellbore stability is essential for the successful execution of directional drilling projects.

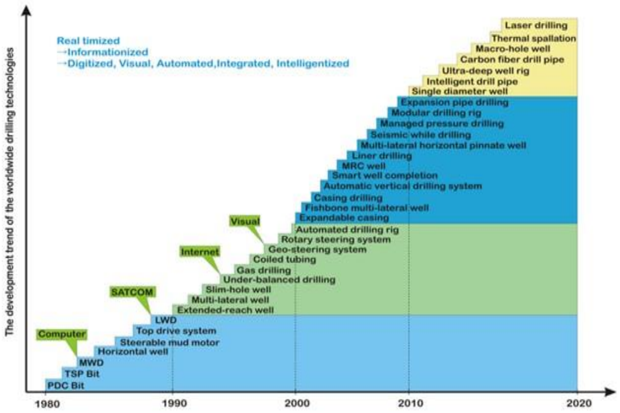

Figure 9. Drilling methods developments [19].

Although rotary steerable systems provide notable performance benefits such as improved trajectory control, enhanced drilling efficiency, and superior borehole quality their widespread adoption is constrained by high costs, operational complexity, and sensitivity to challenging downhole conditions [47]. Table 3 depicts the summary of rotary steerable systems limitations. Their economic justification is generally robust in extended-reach or technically demanding wells; however, in conventional or less complex drilling environments, the cost-effectiveness of RSS remains limited unless lower-cost, application-specific variants are employed.

Table 3. Summary of rotary steerable systems limitations.

Limitation	Description
Capital/Operational Cost	High initial investment; suitable only for complex wells
System Reliability	Vulnerable to downhole dynamics; steep tool-specific learning curves
LIH Cost vs. Frequency	Higher per-unit loss, but lower failure frequency; overall cost reduction in complex wells
Applicability	Best for ERD, horizontal, high-value wells; less optimal for simple environments

7 Conclusions and future directions

The application of advanced drilling methods, such as multilateral drilling, extended reach drilling, and directional drilling, has greatly enhanced the efficiency and cost-effectiveness of oil and gas extraction, especially in challenging reservoirs. These technologies have enabled engineers to access previously unreachable reserves, optimize reservoir drainage, and improve overall production rates. Multilateral wells, for example, are particularly advantageous in low permeability reservoirs, as they increase production by extending multiple lateral branches from a single main bore. Despite the higher initial costs, the substantial increase in recovery and production justifies the investment. Additionally, ERD has transformed the exploration of hard-to-reach reserves, particularly in offshore environments, by facilitating the drilling of wells over long horizontal distances. This advancement has improved production efficiency and reduced the need for costly offshore platforms. As these technologies evolve, the integration of electrified systems and real-time monitoring is expected to significantly reduce operational risks, improve precision, and further optimize well management. Electrically controlled systems will offer greater flexibility and precision compared to traditional hydraulic systems, enabling more efficient fluid flow control and real-time analysis of reservoir behaviour. This is crucial for improving recovery rates and the overall sustainability of operations, particularly in complex, multi-lateral reservoirs. Looking to the future, further innovations in drilling tools and techniques are expected, including wireless downhole communication and inductive coupling for electrical transmission, which will enable more accurate real-time monitoring and control of well conditions. With growing emphasis on environmental sustainability, these innovations will help reduce operational costs and environmental impact, contributing to more sustainable and cost-efficient drilling operations. Moreover, the future of well completion and management will likely focus on enhancing the adaptability of these systems to address the complexities of diverse reservoirs. Research and development will continue to play a crucial role in overcoming challenges related to fluid management, coning control, and reservoir optimization. By incorporating enhanced oil recovery techniques and assisted gravity drainage, multilateral wells will remain a highly cost-effective solution for increasing production while minimizing environmental impact. In summary, the ongoing advancement of multilateral, ERD, and directional drilling technologies will shape the future of oil and gas exploration, making it more efficient, flexible, and sustainable. By addressing key challenges and integrating new innovations, these methods will continue to lead the way in modern oil and gas production, unlocking previously untapped resources while minimizing environmental risks and maximizing recovery potential.

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