DIGITALIZATION OF THE OIL INDUSTRY: SCIENTIFIC ASPECTS AND JUSTIFICATION OF INTELLIGENT TECHNOLOGIES

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Abstract

Most onshore oil fields and offshore deposits located in the Caspian sector of Azerbaijan extend over hundreds of square kilometers. A significant proportion of these fields are situated in challenging operating environments, including high-temperature zones, deep-water areas, and reservoirs characterized by hard-to-recover reserves. These conditions, combined with the growing need to ensure technological and industrial safety, create substantial challenges for the development and operation of oil fields amid continuously increasing global demand for oil and gas. Consequently, oil enterprises require highly reliable digital infrastructure capable of ensuring enhanced operational efficiency, safety, and real-time monitoring of numerous technological devices deployed throughout the field.

In recent years, oil companies worldwide have increasingly relied on intelligent technologies for the management and operation of oil fields. These technologies have proven to be an effective instrument for improving industrial safety, increasing labor productivity, and enhancing the economic efficiency of oil production processes. Modern digital solutions optimize all stages of the operational cycle through the rapid acquisition and processing of production data using advanced analytical systems based on the Internet of Things (IoT). This approach facilitates more efficient reservoir management and improves the overall effectiveness of field development.

The experience of leading international oil companies demonstrates that the implementation of intelligent technologies produces highly reliable and economically efficient results, contributing both to improved hydrocarbon production processes and to cost reduction across individual technological operations.

Keywords: digital industry; intelligent technologies; Internet of Things; robotization; artificial intelligence; digital twins; oil fields

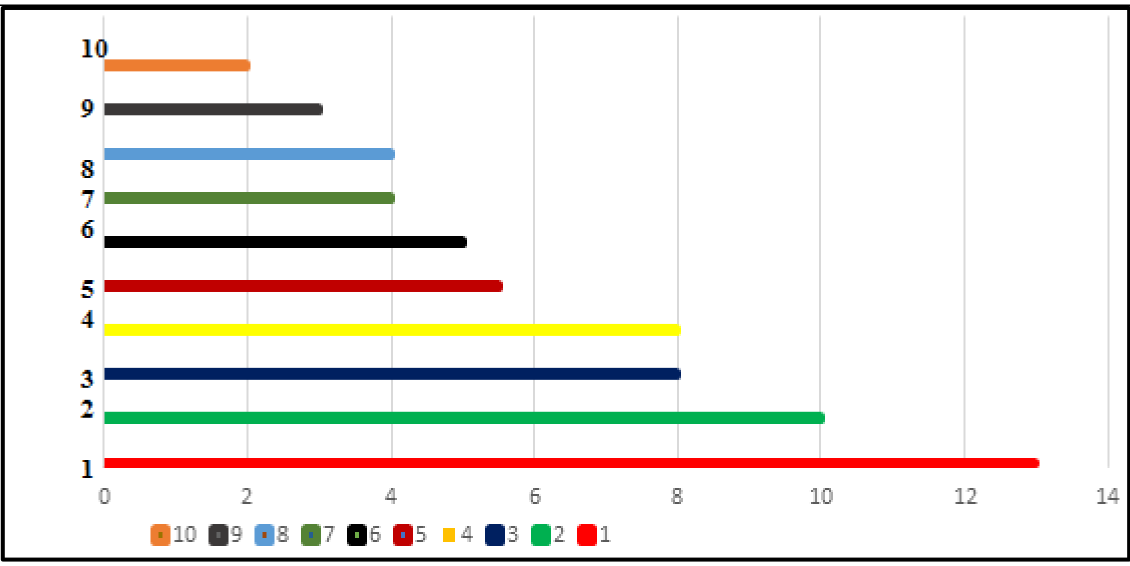
I. Introduction

Given the continuous growth in global demand for energy resources and the necessity of developing oil fields characterized by hard-to-recover reserves, as well as fields at the final stage of production, oil companies increasingly require more efficient oil recovery technologies based on fundamentally new approaches and principles.

The terms *"new production technologies"* or *"advanced manufacturing technologies"* generally refer to technologies and technological processes, as well as machines, equipment, devices, and instruments based on microelectronics or controlled by computer systems and utilized in the design, production, processing, and distribution of industrial products.

In Azerbaijan and internationally, technologies are considered innovative if they are fundamentally new, developed for the first time, and have no domestic or foreign analogues. In addition, such technologies possess qualitatively advanced characteristics that meet or exceed current technological standards and industrial requirements. These technologies are typically based on breakthrough or highly efficient pioneering inventions.

Expert assessments conducted in the United States regarding the most significant advanced manufacturing technologies are presented in Fig. 1.



1 — measurement and precision sensing technologies; 2 — nanomanufacturing; 3 — information technologies; 4 — nanomaterials; 5 — adaptive control systems; 6 — biomanufacturing; 7 — biofuels; 8 — mobile robotics; 9 — technical response systems; 10 — high-efficiency industrial heat recovery technologies.
Figure 1. Significance of Advanced Manufacturing Technologies (U.S. Expert Assessments)

As illustrated in Fig. 1, advanced manufacturing technologies constitute the primary driving force behind the emergence of new markets and the further development of the digital economy. These technologies also represent the technological foundation of the ongoing digital revolution. Among them, intelligent technologies occupy a central position [1-4].

According to Daniel Bell, the new technological paradigm assigns a decisive role to electronic systems for information processing, storage, transmission, and digital transformation. In his view, the implementation of intelligent technologies in industrial production should encompass the following components:

- management control loops, ranging from operational and routine control to strategic and situational management;
- management domains, including financial, labor, production, logistics, customer, and supplier management;
- functional subsystems of the corporate management system;
- management levels, including corporations, subsidiaries, and structural divisions;
- management objectives aimed at reducing production, financial, environmental, and other operational risks and costs, while increasing the reliability and efficiency of industrial systems;
- professional roles and workplaces of employees.

At the same time, intelligent technologies enable the effective transformation of scientific knowledge generated within higher education institutions into a direct productive force of the economy.

Currently, the key technological trends associated with the modern industrial revolution, commonly referred to as Industry 4.0, include:

- the Internet of Things (IoT);
- machine-to-machine (M2M) communications;
- modeling and forecasting based on advanced analytics and big data technologies;
- cloud and fog computing, as well as distributed data storage systems;
- industrial robotization;
- additive manufacturing;
- cognitive technologies;
- advanced human–machine interfaces;
- computer simulation of equipment, materials, and technological processes;
- augmented reality technologies;
- intelligent sensors;
- 3D printing technologies.

The emergence of the global Internet network in 1982 marked the beginning of a fundamentally new virtual environment encompassing digital communication platforms, banking transactions, online commerce, social networks, computer games, and numerous other forms of human activity. As a result, a new integrated model of human interaction has evolved, combining both physical and virtual environments.

This transformation has contributed to the formation of a fundamentally new digital model of global economic development, characterized by the deep integration of information technologies into all spheres of social and industrial activity (Figure 2).

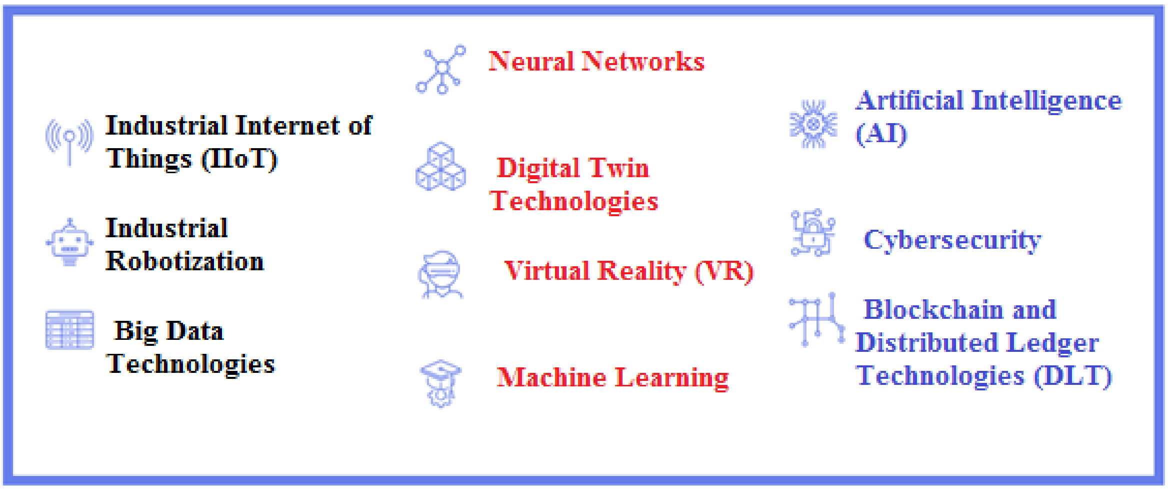


Figure 2. Key Innovative Methods and Technologies in the Modern Oil Industry

In particular, the first Internet-connected device appeared in 1990, when John Romkey introduced a unique toaster that could be remotely controlled via the global network.

Today, the Internet of Things (IoT) is understood as the practical implementation of a network of interconnected physical objects equipped with embedded electronic devices that enable effective interaction with each other and with the external environment. This concept minimizes the need for direct human involvement in a wide range of operations and processes, thereby fundamentally transforming economic and social systems [5-9].

The concept and the term *Internet of Things* were first proposed in 1999 by Kevin Ashton, head of the Auto-ID research group at the Massachusetts Institute of Technology. However, according to analysts from Cisco, the actual emergence of the IoT era dates back to 2008–2009, when the number of devices connected to the global network exceeded the world's population for the first time (Figure 3). At this stage, the "Internet of People" evolved into the "Internet of Thing

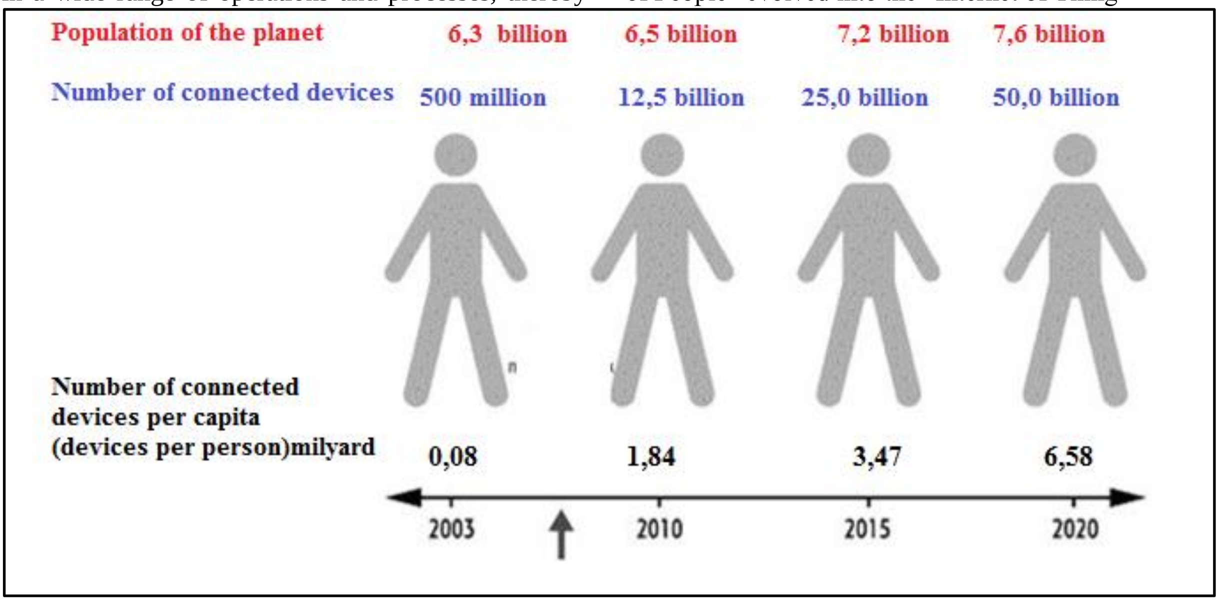


Figure 3. Trends in World Population Growth and the Number of Connected Devices

At present, more than 20 billion diverse devices are already connected to the Internet of Things. On average, there are approximately three connected electronic devices per person worldwide. These typically include smartphones, laptops, and various smart devices such as smartwatches, fitness trackers, connected televisions, or intelligent security systems.

As a result of this large-scale interconnection, the global system already comprises over 2 billion connections among approximately 200 million different devices, and it is projected that this number will reach 28 billion connections by 2030 [10-12].

The real-world IoT ecosystem consists of three main segments, each evolving along its own trajectory:

1.Machine-to-Machine (M2M) communications;

2.Smart systems, where widespread adoption begins with peripheral devices connected via Bluetooth and similar protocols;

3.Context-aware (situational) IoT, comprising traditional household devices enhanced with advanced digital capabilities.

Currently, several key trends characterize the development of Machine-to-Machine communication technologies:

♦Remote nodes are becoming increasingly intelligent, with most devices expected to gain significantly expanded functionality in the near future.

♦.Miniaturization of M2M systems is enabling their application in domains previously considered impractical or infeasible.

♦.High reliability, operational readiness, and system stability are essential features, as many systems operate autonomously without human intervention and are often deployed in remote or inaccessible environments where maintenance is costly or technically challenging.

♦High-speed bidirectional data transmission is a critical requirement, as data are frequently generated by mobile devices and subsequently transmitted for processing and analysis.

II. Some Aspects of the Application of Digital Technologies in the Oil Industry of Azerbaijan

The adoption of digital technologies in the oil and gas sector is driven by the continuous efforts of companies to improve operational efficiency and optimize oil and gas production processes. In this context, diverse production-related information has become a key strategic resource for the management of modern industrial systems, while the level of information technology development significantly determines the competitiveness of oil fields, pipelines, and other production facilities.

Since 2011, the concept of the Fourth Industrial Revolution has been widely introduced into professional discourse. It is defined as the transition toward fully automated digital production systems equipped with intelligent real-time control mechanisms, capable of continuous interaction with the external environment. This paradigm extends beyond individual enterprises and envisions the integration of production systems into a global industrial network for goods and services.

The main drivers of the ongoing digital revolution include the widespread dissemination of computing technologies—primarily personal computers—the ubiquitous expansion of the Internet, and the mass adoption of portable digital communication devices.

As a result, the digital revolution has led to the global transition toward a digital economy, the principles of which are embedded in the conceptual framework of Industry 4.0.

Thus, modern digital society has emerged as a result of the widespread development of mobile services, the Internet, and digital broadcasting, which in turn are based on advances in semiconductors, telecommunications, display technologies, and other fields of information and communication technologies.

The previous industrial paradigm (Industry 3.0) was primarily based on the automation of individual production processes, whereas Industry 4.0 is characterized by the end-to-end digitalization of all physical assets within an enterprise and their integration into a unified digital ecosystem.

Within this framework, Industry 4.0 encompasses the digitalization and integration of the entire product lifecycle, from design and development to logistics, operation, maintenance, and service processes. Accordingly, each manufactured product is expected to have a digital representation, meaning that all related information—including design documentation, production technologies, operational guidelines, maintenance procedures, and disposal instructions—must be digitized and made accessible to both humans and machine systems.

It is also essential that data on all ongoing processes, production stages, components, assemblies, and final products be available in real time to authorized users within a unified digital network. Industry 4.0 requires continuous data exchange among all participants involved in the production chain, including enterprise specialists, equipment, ERP systems, robots, and products.

To ensure this integration, production systems combine hardware components, technological equipment, and logistics systems into a unified cyber-physical environment. A critical element of this architecture is the continuous exchange of production data among all components of the system, enabled by Internet of Things technologies [13-14].

In addition, it should be emphasized that digital oil and gas technologies rely on extremely large volumes of heterogeneous data, commonly referred to as Big Oil Data (BOD). Globally, approximately 2.5 exabytes (10^{18} bytes) of new data are generated daily, of which the oil and gas sector accounts for up to 10%. Moreover, approximately four-fifths of this information—including seismic, geophysical, production, financial, and reporting data—exists in unstructured form.

Under these conditions, cloud computing has become one of the most efficient technologies for data storage and processing. Cloud storage refers to an online data infrastructure in which large-scale industrial datasets are distributed across multiple network-connected servers provided as a service to users. Logically, these resources operate as a single virtualized computing environment, while physically the servers may be geographically distributed across different continents.

Such an architecture enables real-time exchange of production data among authorized participants, significantly improving the quality and speed of managerial decision-making. This, in turn, reduces operational downtime and substantially decreases the likelihood of industrial accidents. In the oil and gas industry, cloud technologies have become a core component of digital infrastructure, primarily aimed at reducing IT-related costs, while also serving as a key enabler for unlocking additional value from advanced digital solutions. As a result, companies with access to accurate and real-time data demonstrate an average annual improvement of approximately 24% in the speed and quality of production decision-making.

As a result, major oil companies worldwide are increasingly adopting digital and intelligent technologies. For example, Shell and TotalEnergies utilize robotic systems, while Chevron and Shell employ drones for inspection and monitoring tasks. Equinor uses 3D visualization technologies, and Chevron applies video analytics to detect pipeline leaks. In addition, BP is implementing large-scale projects on offshore production platforms based on the Industrial Internet of Things (IIoT).

Furthermore, most global oil and gas companies already integrate artificial intelligence, as well as virtual and augmented reality technologies, into industrial operations. In 2018, BP joined the Enterprise Ethereum Alliance, which focuses on the adoption of smart contracts in corporate systems. Even blockchain technology has gained significant attention within the oil industry.

Currently, various oil companies implement proprietary initiatives that can be classified as “smart” or “intelligent manufacturing” projects:

♦“Smart wells” – Smart Wells (Schlumberger);

♦ “Smart operations” – Smart Operations (Petoro);

♦ “Integrated operations” – Integrated Operations (Equinor, OLF);

♦Electronic operations management” – eOperations (North Hydro);

♦Real-time operations management” – Real Time Operations (Halliburton);

♦ “Correct drilling direction” – eDrift (OD);

♦Integrated Asset Operation Model” – IAOM (ADCO);

♦Smart field” – Smart Field (Shell);

♦ “Intelligent field” – i-Field (Chevron);

♦Field of the Future” – Field of the Future (BP);

♦Digital Oil Field of the Future” – DOFF (CERA); “Intelligent field optimization and remote management” – INFORM (Cap Gemini) and others.Конец формы

All these systems are largely similar in terms of their core objectives and operational tasks. They are designed to simulate, with a high degree of reliability, various scenarios in oil and gas production systems and to enable the selection of optimal decision-making strategies, including more efficient utilization of highly qualified personnel within the company[15-18].

The presence of “intelligence” in any complex system—whether biological (human) or engineering-based (such as wells, oil fields, pipelines, etc.)—implies the capability of autonomous regulation and optimization of multiple internal operational parameters in response to diverse and continuously changing environmental conditions or external influences.

This necessitates the implementation of so-called intelligent technologies in the oil industry. Their primary purpose is to maximize the productivity of an expanding well stock, reduce operational expenditures, and accelerate hydrocarbon production while increasing overall output.

In this context, an intelligent technology in an oilfield is understood as an automated control system for oil and gas production operations that ensures continuous optimization of an integrated reservoir model as well as an efficient production management model.

The most promising intelligent oil and gas technologies include drilling, monitoring, and maintenance robotics, low-temperature reservoir treatment technologies, subsea oil production systems, automated (unmanned) platforms, and wireless control systems (Figure 4).

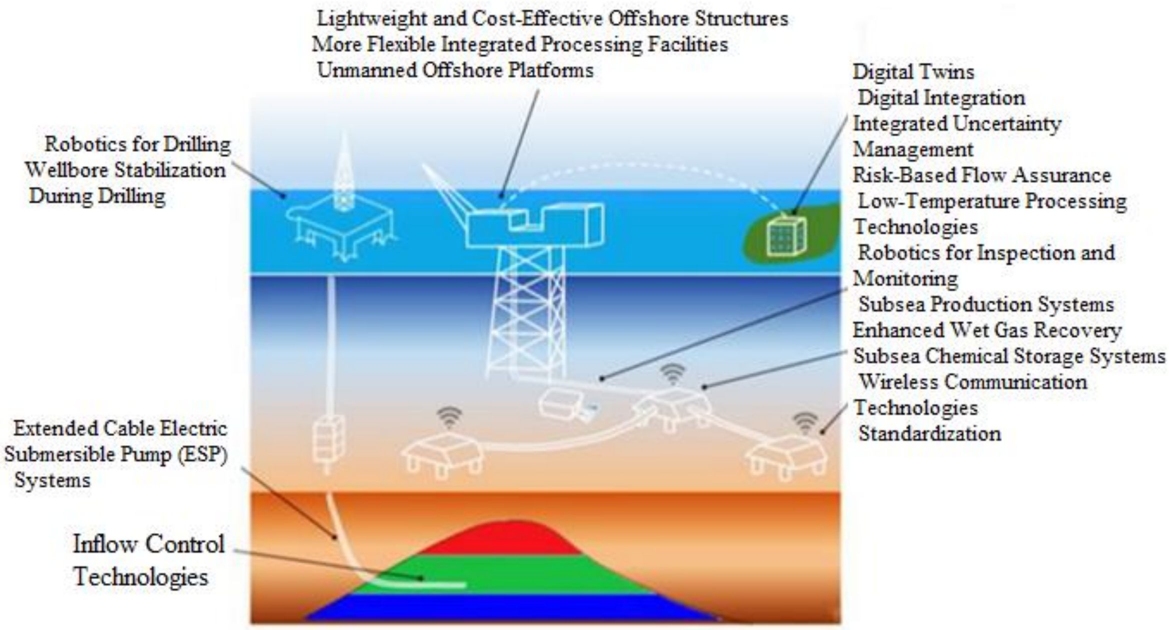


Figure 4. Key Elements of Offshore Oil Production Digitalization

III. Effects of Intelligent Oilfield Technologies

In our view, the use of real-time production data enables digital oil and gas companies to achieve the following objectives:

- expansion of the enterprise resource base;
- increased hydrocarbon recovery rates and oil production volumes;
- reduction in the number of operational incidents, including leaks and emissions;
- improved operational efficiency and enhanced personnel safety;
- optimization of operational activities in oil and gas production, transportation, and processing, as well as across drilling and refining facilities operating in both stationary and field environments.

The principal indicators determining the economic feasibility of expenditures associated with oilfield development, as well as the implementation and operation of intelligent technologies, include [19-24].

- annual economic effect;
- profit growth;
- payback period of capital investments.

Table 1.

Advantages of Intelligent Technologies

Indicators	Field Management Technologies		
	Conventional Automated Technologies (Active Management)	Digital Technologies (Reactive Management)	Intelligent Technologies (Proactive Management)
Increase in Oil Production, %	1,0	4,0	10,0
Increase in Oil Reserves, billion tons	5,0	10,0	15,0
Increase in Oil Recovery Factor (ORF), %	1,0	5,0	10,0
Specific Automation Costs, % of Revenue or per tons	0,5	1,0 – 2,0	2,0 - 4,0
Reduction in Unit Oil Production Costs, %	2,0	5,0	15,0
Labor Productivity Growth, %	1,0	5,0	10,0

It should be noted that, according to expert assessments, the widespread implementation of intelligent technologies could increase the global oil recovery rate from 30% to 50%. According to estimates by Saudi Aramco, the introduction of reservoir nanorobots at mature oilfields could increase the oil recovery factor to 60–70%.

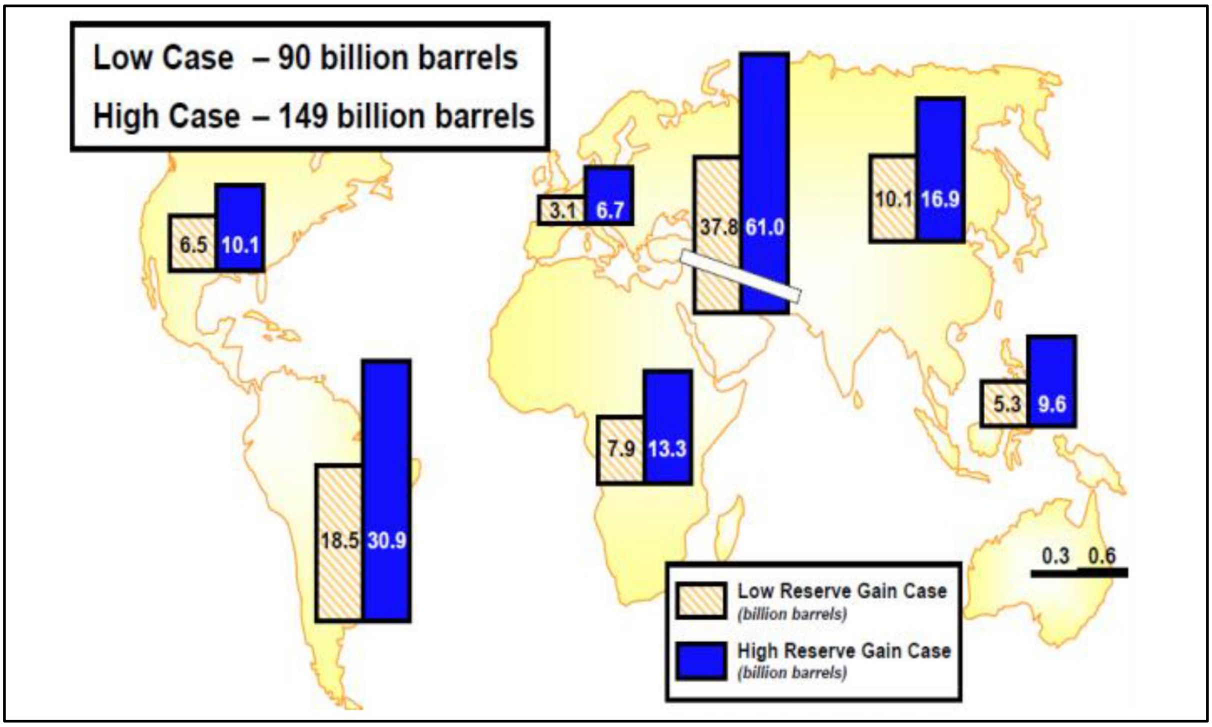


Figure 5. Increase in Hydrocarbon Reserves by World Regions Resulting from the Implementation of Intelligent Technologies (Source: IHS Inc.)

According to estimates by Cambridge Energy Research Associates (CERA), the comprehensive utilization of intelligent oilfield technologies may improve field development efficiency by approximately 2–7%, reduce oil recovery costs by nearly 25%, and increase the productivity growth rate of oil and gas operations by 2–4%.

The economic efficiency of intelligent oil and gas production can be achieved through increased oil and gas output, primarily as a result of:

●reducing downtime in oil production wells;

●minimizing losses of oil, gas, and water through optimized separation, dehydration, desalination processes, and early leak detection within hydrocarbon gathering systems;

●comprehensive optimization of oil production processes.

In particular, within the framework of intelligent oilfield implementation in California operations, field operators can access real-time operational data on tablets while conducting inspections or remaining inside their vehicles, as well as receive alerts regarding situations requiring immediate response. This approach enables personnel to avoid multiple daily visits to each well and instead focus on wells requiring maintenance.

Conclusion

The foundation of the Fourth Industrial ("digital") revolution lies in the processes of economic digitalization, which are leading to radical transformations across entire industries. For example, the widespread adoption of Internet telephony, various messaging platforms, and virtual operators has driven a fundamental restructuring of business models within telecommunications companies. Similarly, the emergence of autonomous and electric vehicles, as well as the development of car-sharing services, is significantly reshaping the traditional structure of the transport sector.

Alongside the expansion of shale resource production, the growing use of renewable energy sources, and the activities of numerous start-ups, these innovations have also had a substantial impact on the oil and gas industry.

It is essential to effectively leverage these still largely untapped opportunities. From a technological perspective, Azerbaijan's offshore oil and gas sector is already well prepared for large-scale digital transformation. It has accumulated a significant volume of production data, established the necessary computational infrastructure for data processing, and benefits from continuously decreasing costs of innovation implementation, as well as an expanding body of practical experience in their application.

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