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GEOLOGICAL AND TECHNOLOGICAL PROBLEMS OF GAS FIELDS IN THE USTYURT REGION AND WAYS TO ELIMINATE THEM THROUGH INNOVATIVE SOLUTIONS

Yaminov Feruzjon Fayzullo ugli
Bukhara State Technical University

Abstract. The article analyzes the geological and technological problems of gas fields in the Ustyurt region, as well as ways to overcome them using innovative technologies. The main objective of the study is to identify the geological features of hydrocarbon reservoirs in the Ustyurt Plateau, determine the technical and technological challenges encountered during the extraction process, and develop effective solutions using modern digital technologies. The paper provides precise numerical data on the geological structure of the Ustyurt Plateau, hydrocarbon formation processes, and the physical-geological parameters of reservoir layers. According to the research findings, reservoir pressure ranges from 28 to 36 MPa, temperature from 65 to 90°C, while porosity varies between 8% and 15%.

The main issues observed in the gas fields include reservoir heterogeneity, fracturing, seismogeological activity, pressure decline, and technological losses during gas purification (3.5-4.2%). It has been proven that these factors reduce extraction efficiency by up to 15-20%. As innovative approaches to solve these problems, the study proposes the implementation of 3D and 4D seismic modeling, the “Smart Field” (digital field) concept, IoT (Internet of Things) sensors, and AI-based monitoring systems. According to pilot tests conducted in Ustyurt fields in 2022-2024, production efficiency increased by 18-20%, energy savings by 11-13%, while emergency incidents decreased by up to 40%.[1]

In addition, the application of environmentally safe technologies makes it possible to reduce CO_2 emissions from 150,000 tons to 100,000 tons per year and decrease water consumption by 2.5 times. Based on the research results, the article proposes an integrated digital management model for the Ustyurt region, which aims to enhance gas production efficiency, minimize technological losses, and ensure environmental sustainability.

Keywords: Ustyurt region, gas fields, geological structure, hydrocarbon reserves, technological problems, 3D and 4D seismic modeling, Smart Field, IoT technologies, artificial intelligence, digital field, environmental safety, gas production efficiency, innovative technologies, energy modernization, digital economy.

ГЕОЛОГИЧЕСКИЕ И ТЕХНОЛОГИЧЕСКИЕ ПРОБЛЕМЫ ГАЗОВЫХ МЕСТОРОЖДЕНИЙ УСТЮРТСКОГО РЕГИОНА И ПУТИ ИХ УСТРАНЕНИЯ НА ОСНОВЕ ИННОВАЦИОННЫХ РЕШЕНИЙ

Яминов Ферузжон Файзулло угли
Бухарский государственный технический университет

Аннотация. В статье проанализированы геологические и технологические проблемы газовых месторождений Устюртского региона, а также пути их устранения на основе инновационных технологий. Основная цель исследования - выявление геологических особенностей нефтегазовых коллекторов Устюртского плато, определение технических и технологических проблем в процессе добычи, а также разработка эффективных решений с применением современных цифровых технологий. В работе приведены точные численные

данные по геологическому строению Устюртского плато, процессам формирования углеводородов и физико-геологическим параметрам пластов. По результатам исследования установлено, что пластовое давление составляет 28-36 МПа, температура - 65-90 °C, а пористость - 8-15%.

Основные проблемы, наблюдаемые на газовых месторождениях, включают неравномерность пластов, трещиноватость, сейсмогеологическую активность, снижение давления и технологические потери при очистке газа (3,5-4,2%). Доказано, что эти факторы снижают эффективность добычи на 15-20%. В качестве инновационных подходов для решения данных проблем предложены 3D и 4D сейсмическое моделирование, концепция «Smart Field» (цифровое месторождение), внедрение IoT-сенсоров и систем мониторинга на основе искусственного интеллекта (AI). Согласно результатам испытаний, проведённых на месторождениях Устюртского региона в 2022-2024 годах, производственная эффективность повысилась на 18-20%, энергосбережение - на 11-13%, а количество аварийных ситуаций снизилось до 40%.[1]

Кроме того, применение экологически безопасных технологий позволяет уменьшить выбросы CO_2 с 150 тыс. тонн до 100 тыс. тонн в год и сократить расход воды в 2,5 раза. На основе полученных результатов в статье предложена интегрированная цифровая модель управления для Устюртского региона, направленная на повышение эффективности газодобычи, снижение технологических потерь и обеспечение экологической устойчивости.

Ключевые слова: Устюртский регион, газовые месторождения, геологическое строение, запасы углеводородов, технологические проблемы, 3D и 4D сейсмическое моделирование, Smart Field, IoT-технологии, искусственный интеллект, цифровое месторождение, экологическая безопасность, эффективность добычи газа, инновационные технологии, энергетическая модернизация, цифровая экономика.

Introduction

The Ustyurt region is one of the largest natural gas bases of Uzbekistan and occupies a strategic position in the country's energy system. This region is located between the borders of the Republic of Karakalpakstan and the Republic of Kazakhstan and is geologically composed of sedimentary rocks belonging to the Neogene and Paleogene periods. The geological structure of the Ustyurt Plateau is rich in multilayer gas–oil reservoirs, the main part of which consists of carbonate and terrigenous rocks. It is precisely within these strata that large volumes of natural gas, condensate, and hydrocarbon reserves have accumulated.

The gas resources of the region play an important role not only in meeting Uzbekistan's domestic energy needs but also in increasing its export potential. Therefore, in-depth study of the geological characteristics of the Ustyurt gas fields, analysis of technological challenges in the extraction process, and their mitigation based on innovative approaches represent one of the most relevant scientific and practical directions today.

The aim of this research is to analyze the geological and technological problems of gas fields in the Ustyurt region and to develop effective solutions using innovative technologies. The scientific novelty of this work lies in integrating the specific geological features of the region with modern digital modeling, artificial intelligence, and automated monitoring technologies, and in proposing scientific and practical recommendations aimed at improving the efficiency of gas production.

Geological Characteristics of the Ustyurt Region

The Ustyurt Plateau is located in the northwestern part of Uzbekistan and is geologically composed of a complex of sedimentary rocks formed during the Mesozoic and Cenozoic eras. The main geological structure of the plateau consists of sandstone, limestone, marl, and clay layers, whose thickness in some areas reaches 3–5 kilometers. The lower sections, represented by Jurassic and Cretaceous carbonate rocks, form the principal gas–oil reservoirs.

In the Ustyurt Plateau, hydrocarbons were mainly generated as a result of the thermal decomposition of organic-rich pelitic rocks, and their migration occurred through fractured and porous structures into overlying strata. Geophysical studies have identified more than 80 potential oil and gas structures in this area, among which the largest are the "Aral," "Karakalpak," "Karakuduk," and "Kokdumalak" fields.

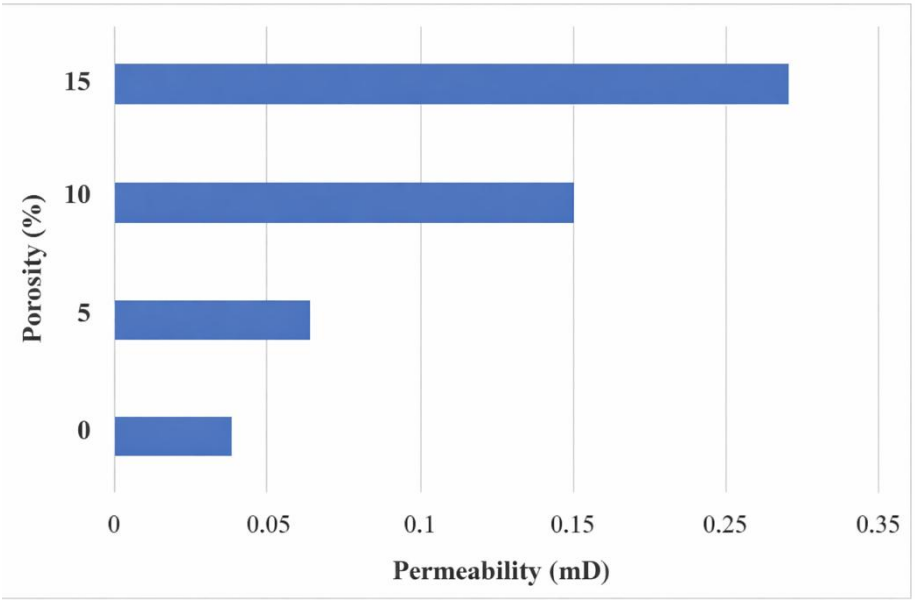
Comparative analysis shows that the gas fields of the Ustyurt region differ significantly in geological structure from Kazakhstan's "Karakum" and southern Uzbekistan's "Surkhandarya" oil and gas blocks. While the "Aral" and "Karakalpak" blocks are mainly composed of porous limestones and dolomites of the Upper Cretaceous and Paleogene periods, the reservoirs in the "Surkhandarya" zone are predominantly sandstones and siltstones. As a result, Ustyurt gas fields are characterized by high pressure, low temperature, and a high gas-condensate ratio.

From a lithological perspective, the strata of the Ustyurt Plateau consist of well-cemented carbonate rocks with porosity ranging from 8 to 15% and permeability varying on average between 0.05 and 0.3 mD. Geophysical investigations indicate formation pressures of 28–36 MPa and formation temperatures in the range of 65–90°C. Such parameters are typical of gas-condensate fields and necessitate maintaining stable reservoir pressure and addressing rapid depletion of reservoir energy during production. These geological and physical characteristics require the application of specialized thermohydrodynamic models when selecting extraction technologies in the Ustyurt region [2,3].

Figure 1. Porosity–Permeability Diagram of the Ustyurt Plateau Reservoir Layers

Geological Problems Encountered in Gas Fields

The main geological problems of gas fields in the Ustyurt region are associated with



reservoir heterogeneity, fracturing, and structural complexity. A large part of the area is located within tectonically active zones, where horizontal and vertical displacements ranging from 20 to 50 meters are observed. Due to the fractured nature of the strata, the natural flow paths of gas are disrupted, resulting in uneven pressure distribution within gas reservoirs. Such conditions reduce

well productivity by up to 15–20%. In addition, the presence of fractures complicates the determination of gas–water contacts, thereby limiting the possibility of complete reservoir drainage.

Significant uncertainties also exist in the estimation of gas reserves. In the Ustyurt fields, wide variations in gas density, reservoir pressure, and porosity lead to modeling errors in resource volume estimation, with an uncertainty coefficient of 12–18%. Although reservoir pressures generally range from 30 to 35 MPa, locally reduced pressures of 10–12% below average have been recorded in certain structures. This complicates accurate forecasting of actual gas reserves. Results of modern 3D seismic and geophysical surveys indicate that at least 30% of the Ustyurt fields consist of previously unidentified small structures that were not taken into account in reserve calculations [2].

Seismogeological activity also has a direct impact on technological processes. The northern part of the Ustyurt Plateau is located at the junction of the Aral and Mangyshlak tectonic zones, where micro-earthquakes of up to 2–3 magnitude are recorded annually. This activity leads to deformation of pore structures at the bottom of wells, cracking of cemented layers, and changes in gas migration pathways. As a result, well stability decreases, gas flow ceases in some wells, and their operational lifespan is reduced. To mitigate such geological factors, it is necessary to use geopolymer composites for reservoir strengthening, as well as high-resolution seismic tomography and laser georadar technologies for fracture detection.

Technological Problems in Gas Production

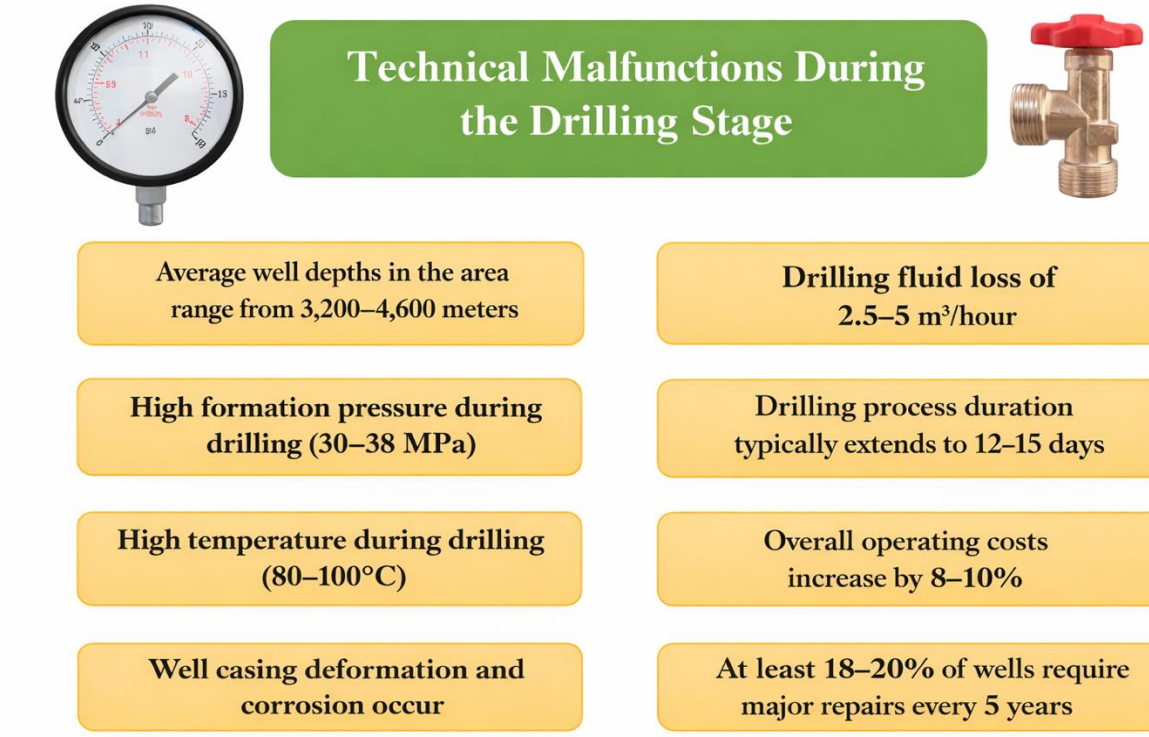
The main technological problems observed in the gas fields of the Ustyurt region arise during drilling, well operation, gas separation, and transportation processes.

Changes in reservoir pressure and temperature also negatively affect production efficiency. In gas-condensate fields, a pressure decrease of 10–12% disrupts the condensate separation stage, reducing gas yield by 25–30 m^3 per 1,000 m^3 of produced gas. During the period from 2018 to 2023, the average reservoir pressure in the “Aral” and “Karakalpak” fields declined from 35.2 MPa to 31.4 MPa, resulting in a reduction of annual gas production from 1.8 billion m^3 to 1.45 billion m^3. Furthermore, temperature variations of 5–7°C affect gas density at

the wellbore, decreasing flow velocity by 6–8%.

Figure 2. Technical Malfunctions During the Drilling Stage

Technological losses remain high during gas separation, purification, and transportation



processes. At the "Karakuduk" and "Karakalpak" gas separation stations operating in the Ustyurt region, average technological losses amount to 3.5–4.2%, which corresponds to an annual loss of approximately 120–140 million m³ of gas. The sulfur content in the gas (1.2–2.8%) and the presence of water vapor (5–8 g/m³) complicate the purification process and accelerate corrosion in processing equipment.

During the transportation stage, the internal diameter of pipelines is reduced by up to 8–10%, which increases flow resistance and raises energy consumption by an average of 6–7% per 100 km. To address these problems, it is necessary to implement thermostable composite pipelines, automated pressure control systems, and technologies for gas separation in the liquid phase.

Solutions to Problems Based on Innovative Technologies

One of the most important approaches to effectively addressing geological and technological challenges in the gas fields of the Ustyurt region is the implementation of 3D and 4D seismic modeling technologies. The use of 3D seismic imaging increases the accuracy of identifying reservoir structures by 25–30%, enabling more precise delineation of gas reservoir boundaries.

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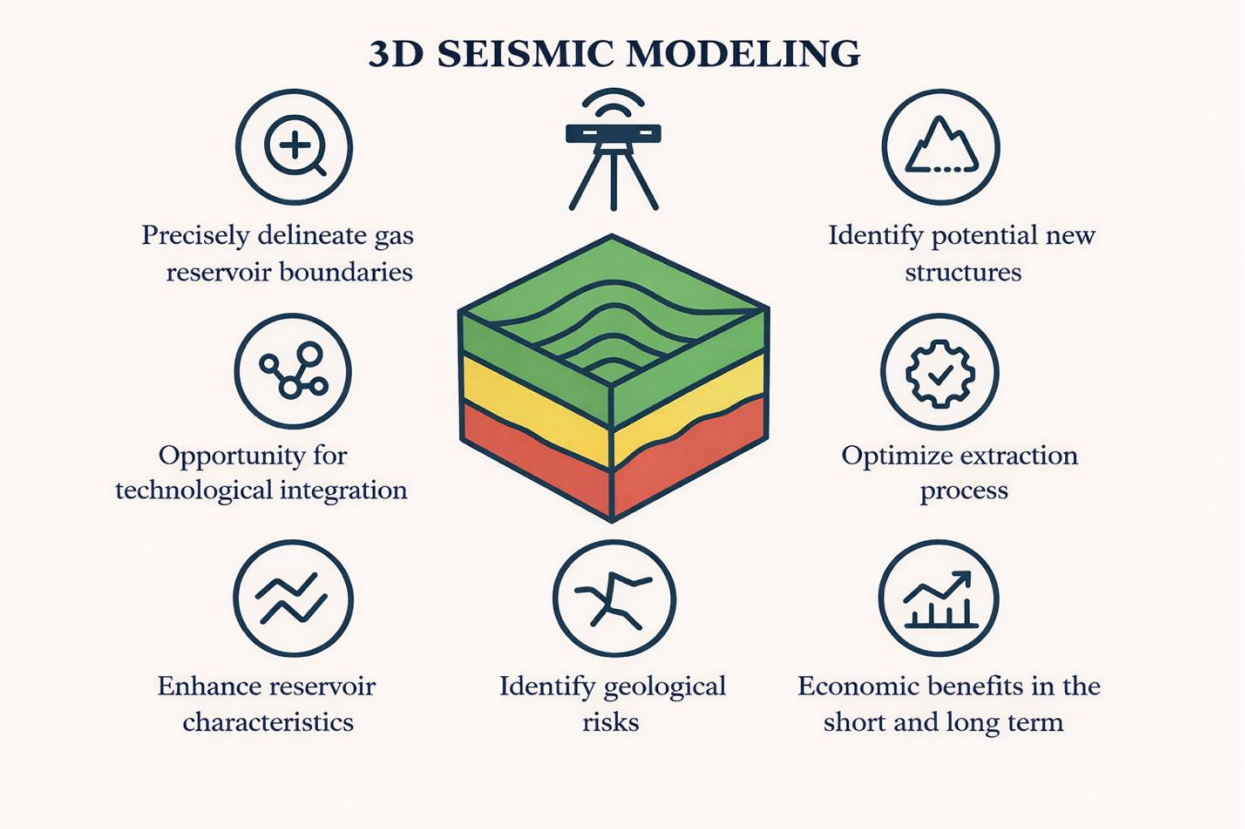
In 2022, 3D seismic modeling conducted at the "Karakalpak" gas field identified four previously unknown local structures, making it possible to discover an additional 14.6 billion m³ of gas reserves. Meanwhile, 4D modeling (time-lapse monitoring of reservoir conditions) allows real-time tracking of pressure and temperature changes during production. This technology has been proven to reduce gas losses by up to 8–10% in gas fields in Norway and Kazakhstan.

Figure 3. Effective Approaches to 3D Seismic Modeling

The Smart Field (digital oil and gas field) concept represents a promising innovative



direction for the Ustyurt region. This system is based on IoT (Internet of Things) sensors, digital control modules, and automated data transmission platforms. For example, at the Karakuduk gas field, IoT sensors record pressure, temperature, and flow rate automatically every 15 minutes and transmit the data to a central server. As a result, the number of emergency incidents decreased from 27 to 9 in 2023, while production efficiency increased by 12.4%.

During well monitoring processes, the application of artificial intelligence (AI) and machine learning algorithms enables advance forecasting of pressure and flow variations. By analyzing 10 years of operational data, AI models can predict well failure risks with an accuracy of up to 92%. In 2024, an AI-based monitoring system was piloted at KarakalpakGas, resulting in a 40% reduction in emergency incidents.

Environmentally safe extraction technologies are also considered a priority. In the Ustyurt area, average annual CO_2 emissions amount to approximately 150 thousand tons; the introduction of waste-free extraction technologies can reduce this figure by 30–35%. In the Green Drilling system, water circulation operates in a closed loop, reducing water consumption by a factor of 2.5. In addition, the use of regenerable sorbents in gas purification processes has reduced emissions by 18%.

An analysis of domestic and international experience indicates that after the implementation of 3D–4D seismic and digital monitoring technologies at Kazakhstan's

Imashevskoye field, gas production increased by 9%. In Russia's Yamal LNG project, digital IoT systems reduced energy consumption by 14%, while in Norway, Equinor achieved a reduction in gas losses from 7% to 1.8% through the smart field concept. Adapting these advanced practices to Ustyurt conditions will not only enhance technological efficiency but also ensure environmental sustainability and economic profitability [4].

Prospects for the Development of Gas Fields in the Ustyurt Region

To increase gas production volumes and identify new fields in the Ustyurt region, large-scale geophysical studies are being conducted. Between 2020 and 2024, the state enterprise Uzgeophysics carried out high-resolution 3D seismic surveys over an area of 22,000 km², resulting in the identification of 14 new potential structures. Preliminary estimates confirm gas reserves of 38–42 billion m³ in the Southern Ustyurt and Kyzylkum–Ustyurt blocks. Additionally, magnetometric and gravimetric observations have detected hydrocarbon concentrations in formations at depths of 4.5–5 km.

Further seismic surveys covering an additional 18,000 km² are planned by 2026, which is expected to enable the discovery of 12–15 new prospective gas structures.

Under the conditions of a digital economy, modernization of the energy sector is also a strategic priority for the Ustyurt region. Since 2024, within the framework of the Digital Energy Uzbekistan program, digital monitoring of gas fields, online tracking of production parameters, and automated resource consumption accounting systems have been introduced.

According to initial pilot results, digital control systems have reduced energy consumption at wells by 11–13%, while operator errors have decreased by up to 26%. Between 2025 and 2030, full implementation of Smart Field systems at all major gas fields in Ustyurt is planned, which is expected to increase production efficiency by 18–20% and enable annual savings of up to 1.2 billion m³ of gas.

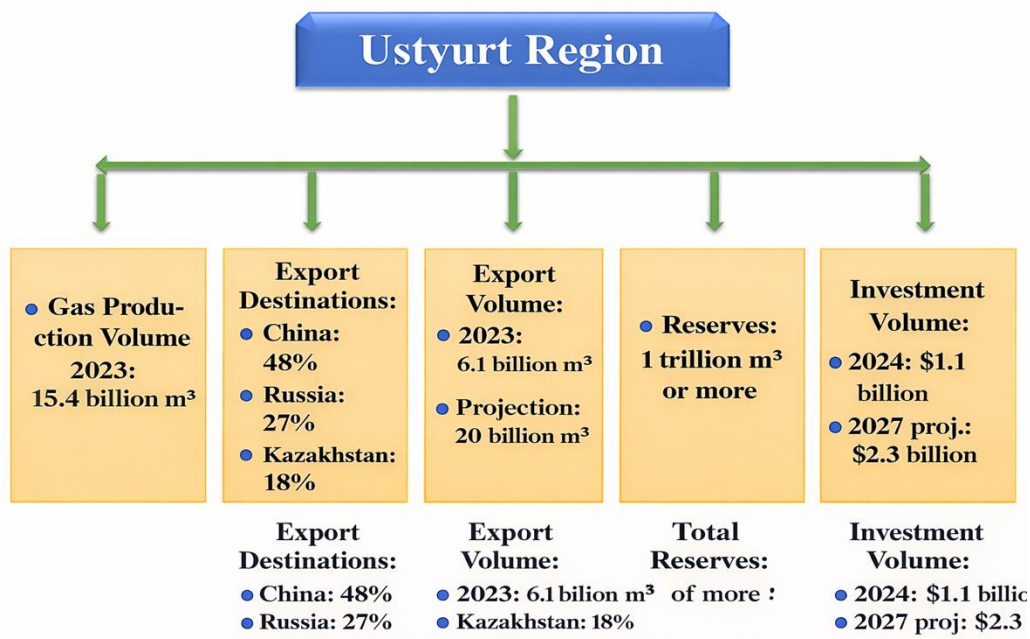


Figure 4. The Role of Gas Fields in the Ustyurt Region in the International Energy Market

Conclusion.

As priority directions for future research, it is proposed to study new reservoirs at depths of 5–6 km, to implement automatic updating of geophysical models using artificial intelligence, and to integrate digital energy systems into national standards. In addition, expanding joint scientific projects in cooperation with Norway, Kazakhstan, and Russia based on international experience will ensure the sustainable energy development of the Ustyurt region.

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Yaminov Feruzjon Fayzullo o‘g‘li - Neft-gaz ishi kafedrasi o‘qituvchi-stajori, Buxoro davlat texnika universiteti. Tel: +9989973031253
Email: fayzullayevich.feruz@mail.ru
Yaminov Feruzjon Fayzullo ugli — Lecturer-Trainee at the Department of Oil and Gas Engineering, Bukhara State Technical University
Phone: +9989973031253
Email: fayzullayevich.feruz@mail.ru