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Offshore Hydrocarbon Resources

Sustainable Development and Long-Term Forecasting

Edited by
Alexey Cherepovitsyn and Alina Ilinova

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About the Editors

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Preface to "Offshore Hydrocarbon Resources: Sustainable Development and Long-Term Forecasting"

Dear colleagues!

The purpose of this book is to discuss the current state, problems, and prospects of hydrocarbon resources development on the Arctic shelf. This book examines economic, ecological, geological, and technological aspects of Arctic marine oil and gas resources exploration and development. Important issues covered in the book are safety and ensuring the sustainability of the energy sector. Studies presented in the book address issues of ecologically balanced and socially sustainable development of marine and coastal territories of the Arctic.

The book is intended for researchers interested in the development of marine resources, as well as for a wide range of readers.

A number of articles have been published by the authors from Saint-Petersburg Mining University (Russia), as well as by the authors from George Washington University (USA), University of Messina (Italy), Norwegian University of Science and Technology NTNU (Norway), Qingdao University of Technology (China), Federal University of Rio de Janeiro (Brazil), University of KwaZulu-Natal (South Africa), International Institute for Applied Systems Analysis (IIASA) (Austria), University of Sialkot (Pakistan), Russian Academy of Science (Russia), Russian Geological Research Institute (Russia).

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Article

The Future of Energy and the Case of the Arctic Offshore: The Role of Strategic Management

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Abstract: As risk and uncertainty factors have become more prominent in the already volatile energy market because of the COVID-19 pandemic, the development of Arctic hydrocarbon resources has become a debatable issue. At any rate, oil and gas companies need to improve their strategic management systems (along with the development of technologies) for the successful implementation of such complex projects. The purpose of this study was to propose the conceptual basis for transforming strategic management and planning systems of oil and gas companies so that they can successfully face global challenges when implementing offshore oil and gas projects in the Arctic as well as provide more sustainable energy sources. The article discusses the current situation with Arctic initiatives and the results of an analysis of price instability in the energy sector, along with an analysis of several megatrends affecting oil and gas companies. All this allows for presenting a conceptual vision of how a strategic management system should be transformed in order to become able to meet the requirements for implementing Arctic projects, with the emphasis being placed on sustainability, management requirements, and the key principles. The research is based on the fundamentals of strategic management and strategic planning and relies on methods such as desk study, content analysis, event analysis, comparative analysis, and factor analysis.

Keywords: arctic; oil and gas; offshore; energy; strategic management; global disturbances; uncertainty; hydrocarbons; strategic planning; projects; global trends

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1. Introduction

Since 2008, when the U.S. Geological Survey (USGS) completed an assessment of oil and gas resources in the Arctic, hydrocarbon deposits in this region have been attracting increasing attention. According to rough estimates, the Arctic potentially contains about 90 billion barrels of oil reserves, 50 trillion cubic meters of gas reserves, and 44 billion barrels of gas condensate, which constitutes approximately 16%, 30%, and 26% of the world's undiscovered hydrocarbon resources, respectively [1]. About 84% of them lie offshore in the Arctic's seas [2].

In general, reserve estimates that have been conducted in different countries and by various organizations vary significantly because only preliminary exploration operations have been carried out. However, one thing is clear: the Arctic contains a huge volume of hydrocarbons.

Russia is one of the key players in the Arctic and has ambitions to continue developing its hydrocarbon Arctic deposits [3–5]. Russia's Arctic hydrocarbon resources are estimated to consist of 13 billion tons of oil and about 86 trillion cubic meters of gas. However, only a small portion of this huge volume is currently categorized as reserves (1/20 of the oil resources and 1/8 of the gas resources) [6]. Arctic offshore oil and gas reserves are concentrated in two seas (the Barents and Kara Seas) where a lot of geological exploration has been done in recent years [6,7]. Such a volume of proven reserves and a huge resource potential indisputably confirm that the Russian Arctic is and will be an area of significant interest and concern on a global scale.

While oil prices grew and maintained a positive trend (from 2010 to 2014), the experts' assessments of the future of Arctic offshore oil and gas projects were optimistic, and countries (including Russia) had ambitious plans. For instance, in 2012, it was planned to launch full-scale gas production at the Shtokman field, with its reserves being estimated at about four trillion cubic meters [8]. However, the project was suspended. According to the Russian experts' estimates that were conducted in 2016, oil production should be launched at the Arctic offshore Dolginskoye field with oil reserves of 236 million tons by 2021–2023 [7]. However, according to the latest data, the start of production operations has been postponed [6]. In addition to the favorable price situation, the heightened interest in Arctic hydrocarbons at that time (as well as now) stemmed from the gradual depletion of conventional oil and gas reserves in both Russia and the world as a whole.

However, from 2014 to 2016, oil prices demonstrated a downward trend that made oil and gas companies all over the world revise their plans to start operations in the Arctic. For instance, Royal Dutch Shell announced the termination of its expensive Arctic program (around $7 billion of investment over a period of nine years) in 2015 [9]. The Russian oil and gas industry, in addition to the unfavorable pricing trends, came under the influence of the U.S. and EU sanctions [10–12], which had a major negative impact on Russian oil and gas projects including Arctic ones, because many of them were planned in cooperation with foreign companies. In 2016, Russia introduced a moratorium on issuing new licenses to companies that planned to operate offshore in the Arctic. In 2020, access to the Arctic shelf was still available only to state-controlled producers, namely Gazprom and Rosneft. Granting access to private companies is still being discussed.

The only offshore oil project that has been launched full-scale in the Russian Arctic is the Prirazlomnaya platform with total recoverable reserves of over 70 million tons of oil. Over six years (2014 to 2020), 13 million tons of Arctic Oil (ARCO) were produced and 19 wells were drilled (out of the 32 planned) [6,13]. ARCO oil has a high density (about 910 kg/m^3), which increases the demand for such oil in the European market [14]. Several other Russian Arctic offshore projects are at various stages of implementation, and their prospects remain unclear today [15].

In the context of the unfavorable price trends (starting from 2014), experts have estimated that large-scale offshore oil and gas production in the Arctic would be possible only after 2035 [7]. The new Energy Strategy of the Russian Federation for the period until 2035 (Energy Strategy to 2035) [16] adopted in June 2020 also declares that the key growth in hydrocarbon production in the Arctic is expected to happen after 2035. The Russian government sees the exploitation of its Arctic oil and gas reserves as the crux of its Energy Strategy to 2035. However, the ongoing global economic crisis can significantly change the prospects of offshore oil and gas production in the Arctic.

The most promising Arctic offshore oil project is the Dolginskoye field, with an estimated annual capacity of about four million tons of oil. By 2019, four exploration wells had been drilled [6]. According to experts, the field is elongated, which increases capital expenditures (CAPEX) as the use of two, rather than one oil production platform, is required [6]. In 2019, it was planned that production would start in 2031. However, given the new conditions, there is a possibility that the timing will be reviewed. As for offshore gas production in the Arctic, Gazprom Neft hopes to start operating the Kamennomysskoye field in 2025 [17].

It is obvious that the development of Arctic hydrocarbon resources is highly dependent on energy prices [18]. When they go down, Arctic offshore projects are put on hold. In 2020, the situation was exacerbated by the COVID-19 pandemic, with average oil prices plummeting and West Texas Intermediate (WTI) crude oil prices dropping below zero as storage facilities became scarce [19].

In addition to price volatility, which has been exacerbated by the pandemic, oil and gas companies are developing in an unstable environment [20,21]. Global megatrends such as a high degree of uncertainty in the business environment, energy transition, the rapid development of technologies and digital solutions, increased competition, the growing role of environmental and social aspects as well as the impact of macroeconomic and geopolitical aspects require that companies make changes in their operations including making adjustments to their management systems. It is extremely important to note that experts predict a decrease in the share of oil in the global energy mix [22,23] and rapid growth in alternative energy sources. At the same time, experts claim that it is impossible to replace the majority of hydrocarbons with other energy sources in the near future [24]. Scholars also discuss the prospects of hydrogen initiatives in the context of the global sustainable energy agenda [25].

According to the World Energy Council's report titled Decoding New Signals of Change (2020 World Energy Issues Monitor) [20], which was prepared with the participation of more than 3000 energy leaders from 104 countries, there are five categories of challenges in the energy sector that are encountered in the transition period: macroeconomic risks, business environment, geopolitics, energy vision, and technology [20]. Among the main findings of this study are the statements that "macroeconomic and geopolitical issues drive critical uncertainty", and "technology issues drive action priorities" [20].

According to experts, the energy sector will undergo significant changes after the COVID-19 pandemic. It may result in improved financial positions of businesses that are not directly related to the volatile oil and gas market, serious financial implications for private oil companies as well as market concentration and consolidation [19].

However, despite the current instability and the ongoing transformation of the energy sector, the Russian Arctic will remain an area of significant interest for both domestic and international oil and gas companies. The Russian government confirms its intention to support offshore oil and gas production in the Arctic and strengthen the country's position in the promising hydrocarbon province [16].

Even if the share of oil in the global energy mix does decrease, we believe that Arctic offshore oil fields will still be in demand since oil is and will be a raw material for such a promising industry such as petrochemistry. As for offshore gas fields, gas is an environmentally friendly type of fossil fuel that serves as a raw material for the promising sector of natural gas processing.

Today, the commercial performance of Arctic oil and gas projects depends on global oil prices, the availability or lack of state benefits, and the volumes of CAPEX and OPEX. CAPEX and OPEX largely depend on the level of technology development. Global prices and technological development are two crucial aspects that can reduce costs, primarily operating ones. In addition, we believe that strategic management issues are of great importance to hydrocarbon production in the Arctic.

All of the above emphasizes the relevance and importance of a study devoted to the peculiarities and prospects of developing Arctic offshore hydrocarbon resources and strategic management issues associated with this process.

As for studies that are relevant to the issue of hydrocarbon production in the Arctic and strategic management approaches to this activity, they can be divided into three groups: (1) strategic management fundamentals; (2) global trends affecting the development of the oil and gas industry; and (3) trends in offshore oil and gas production in the Arctic.

The theoretical framework (studies in the first group) of the research includes the generally recognized principles and approaches to the strategic management of industrial companies [26,27], that focus on issues such as strategic planning and forecasting for strategic decision making [28,29], strategic business management in turbulent environments [30–32], creating competitive advantages for industrial companies [33], strategic analysis (industry analysis; analysis of resources and capabilities) [34], and modern approaches to strategic planning in the energy sector [35,36], etc.

Based on an analysis of the studies in the first group, we can conclude that (1) the strategic management framework that has been developed so far is mainly focused on industrial enterprises, while Arctic oil and gas projects are complex and industry-specific systems; and (2) these approaches do not take into account new trends and realities of the energy sector. In this regard, the fundamentals of strategic management must serve as a foundation for developing the principles of strategic management and strategic planning applied to hydrocarbon production in the Arctic, but the specifics of Arctic projects and megatrends in the energy sector should be taken into account.

By reviewing the studies in the second and third groups, we analyzed how these specifics can influence strategic management decisions. We studied global megatrends in the energy sector and the influence of the COVID-19 pandemic on the oil and gas industry [19–22,37–41], and present the results of this analysis in Section 3.2. We also studied the current hydrocarbon agenda [11,12,17,18,42,43] and tried to take into account all modern trends.

The identified gap in academic research allowed us to formulate the purpose of the paper presented below.

2. Materials and Methods

The purpose of this paper was to study the features and prospects for the development of strategic management and planning systems for offshore oil and gas projects in the Arctic against the background of global disturbances, a high degree of uncertainty, and their intensification during the COVID-19 pandemic as well as the importance of sustainability in the energy sector.

The research hypothesis is based on the assumption that oil and gas companies operating in the energy sector, which is highly turbulent and undergoing significant change due to a number of global megatrends, should improve their systems of strategic management and planning in order to reduce their dependence on global disturbances and be able to timely implement strategically important projects. Offshore oil and gas projects in the Arctic are the focus of this research.

In this paper, we raise the following research questions:

1. What are the main factors causing instability in the energy sector? What are the main global megatrends affecting the strategic development of oil and gas companies?
2. What are the main directions for transforming strategic management and planning systems used in offshore oil and gas projects that are affected by global disturbances?

To achieve our goal and address the questions above-mentioned, our research was structured as follows:

1. We started with a study of oil price volatility and an event analysis of oil market trends, accompanying them with a discussion on break-even points of offshore oil and gas projects in the Arctic.
2. We continued by identifying the main global trends affecting the strategic activities of oil and gas companies and the challenges that oil and gas companies face.
3. As a result, we present a vision of how strategic management and planning systems can be transformed to reduce the company's dependence on a highly turbulent environment and increase its preparedness for implementing complex offshore projects in the Arctic.

The study is mostly analytical, and the analysis presented is qualitative. During the research, we turned to qualitative approaches such as meta-synthesis and content analysis [44,45]. The first approach helped us to synthesize primary qualitative case studies for achieving the purpose of the study. The steps of this approach such as research question design, identification of relevant studies and creation of inclusion criteria, and synthesis on an across-study level, among others, provided a methodological framework for a qualitative case study analysis. In addition, relevant statistical data and media sources on the topic were used. The main quantitative data sources were statistics provided by **British Petroleum** (BP) and the Ministry of Energy (Russia). As for academic literature, we used the Science Direct and Scopus databases (full access).

When conducting the research, a comprehensive desk study was carried out to collate currently available information on aspects such as general trends in oil and gas market development, global megatrends and challenges affecting the oil and gas sector, oil price volatility, and prospects for hydrocarbon production in the Arctic in pandemic and post-pandemic scenarios. To analyze the latter, we focused on reports provided by energy (oil and gas) companies and organizations since the development of Arctic projects in such scenarios has not yet been presented in academic literature.

As for particular methods, we employed event, comparative, situational, and causal analyses along with the methods of aggregation, decomposition, and systematization. When developing the basic principles of strategic management and planning for oil and gas companies, we focused on the generally accepted strategic management and strategic planning fundamentals for industrial companies.

3. Results

3.1. Volatility in Oil Prices and the Break-Even Point of Offshore Oil and Gas Projects in the Arctic

As noted above, price volatility in the energy sector is one of the key aspects affecting the future of oil and gas projects in the Arctic.

In general, oil (and gas) prices are the most discussed of all prices for commodities on global markets. In recent decades, a bi-directional relationship has been observed: on one hand, oil prices react to what is happening in politics and the global economy; on the other hand, the most important events in the global economy and politics are connected with oil [46]. These include the following: the rapid increase in shale oil and gas production in the United States [47,48]; sanctions against Russia and its oil and gas sector [10]; the ongoing conflicts in Libya, Iraq, and other countries; accelerating technological progress, which makes it possible to develop unconventional oil and gas fields; heated discussions about global climate change, the need for energy transition and relying more on alternative energy sources, etc. [38,46].

Figure 1 shows thee changes in Brent crude oil prices from 1984 to 2020.

Figure 1. Brent spot prices 1984–2020, USD per barrel. Source: Created by the authors, data from [49,50].

Over the past 35 years, four significant drops in oil prices can be noted, the analysis of which is presented in Table 1. These price drops are linked to events affecting the changes in oil prices on the global market.

Table 1. Event analysis comprising changes in oil prices.

Period	Changes in Oil Prices	Average Annual Brent Prices, USD/Barrel	Events that Caused Prices to Drop
		1st price drop	
1985–1986	The price for Brent crude plummeted from a record high of more than $110 per barrel that was reached in 1980, decreasing by almost ten times by 1986.	1985–28 1986–14	Oversupply of oil production, OPEC's rejection of fixed prices and the introduction of Netback pricing, growth in oil production in Saudi Arabia, political events in oil-producing countries
		2nd price drop	
Second half of 2008	Prices decreased by three times from the all-time record level of $140 per barrel in June 2008 to $42 per barrel in January 2009.	2008–97 2009–62	Global economic crisis
		3rd price drop	
2014–2015	Prices decreased by three times from $105 per barrel in June 2014 to $48 per barrel in January 2015 and then to $34 per barrel in January 2016.	2014–99 2015–52 2016–44	Several events were responsible (political and other events in the Middle East, the crisis in the Chinese stock market, etc.), the main of which was the technological progress in the field of shale oil production in the United States (which resulted in signing the OPEC+ agreement in 2016)
		4th price drop	
4.1 January–May 2018 4.2 February–April 2020	A decline in oil prices from $80 per barrel in October 2018 to less than $60 per barrel in December 2018, with a short-term recovery and a decline to $20 per barrel in March 2020.	2018–71 2019–64 2020–41 [1]	4.1—Growth in shale oil production in the United States and the revision of the OPEC+ deal; 4.2—The spread of coronavirus with consequences for the global economy and the termination of the OPEC+ deal (as a result, a new OPEC+ agreement was signed in 2020)

Source: Created by the authors, data from [10,49–54].

The fall in oil prices in 1986 was followed by a 13-year period of decline, with oil prices reaching a peak of $24 in 1990 and a low of $13 in 1998. The latter was due to the Asian financial crisis [49]. Since 2000, oil prices have gradually recovered, reaching their maximum in 2008 before the second fall, after which they grew again before the third fall in 2014. The growth in oil prices from 2010 to 2011 was associated with the onset of the Arab Spring [49], and their recovery since 2016 was the result of signing the OPEC+ agreement that came into force in 2017. Oil prices continued to grow gradually, reaching a five-year record high of more than $80 per barrel in October 2018. However, a new increase in shale oil production destabilized the market in 2018, which caused another decline in prices, which only worsened due to the COVID-19 pandemic and reached record low levels [39].

Oil price volatility became especially acute during the COVID-19 pandemic, which inexorably influenced the energy sector and the entire global economy [19], threatening the efficiency of not only Arctic projects, but the overall operations of oil companies. The

[1] For nine months of 2020 based on [50].

world's largest oil companies reacted by trying to improve their operational activities as much as possible. For example, Sinopec (China) launched a "100-day campaign to tide over difficulties and improve performances" aimed at solving basic problems, optimizing the system, preventing and controlling risks, and using all the opportunities to overcome the crisis [55]. Despite the fact that the operating profit of the company in 1H2020 decreased by 31% compared to the same period in 2019, this can be considered as a positive trend given the serious crisis that directly affected the energy sector [55].

Obviously, companies and projects with high oil production costs were in the most vulnerable position. Among them were companies producing shale oil in the United States; according to rough estimates, their production costs amounted to $50 per barrel [56]. According to the estimates that were made by the International Energy Agency (IEA) in mid-2014, the break-even point of shale oil projects in the United States is around $80 per barrel [43]. Experts claim that recent events may affect the global oil market after 2020 [19]. Undoubtedly, such changes pose a serious threat to the future of offshore oil and gas projects in the Arctic.

The situation with Arctic oil and gas projects is similar [18]: operating projects were especially vulnerable during the period of record-low oil prices, while planned ones became more controversial. Figure 2 shows the changes in Brent crude oil prices from 2010 to 2020 along with a forecast for 2021 as well as changes in the break-even point of Russian and Norwegian Arctic offshore oil and gas projects (Norway's Johan Sverdrup project in the North Sea and Johan Castberg project in the Barents Sea). Oil price forecasts for 2021 are presented based on data from the Energy Information Administration (EIA) and the United States Department of Energy (the forecast is about $50 per barrel) as well as the International Monetary Fund (IMF) and the Organization for Economic Co-operation and Development (OECD) (the forecast is about $40 per barrel).

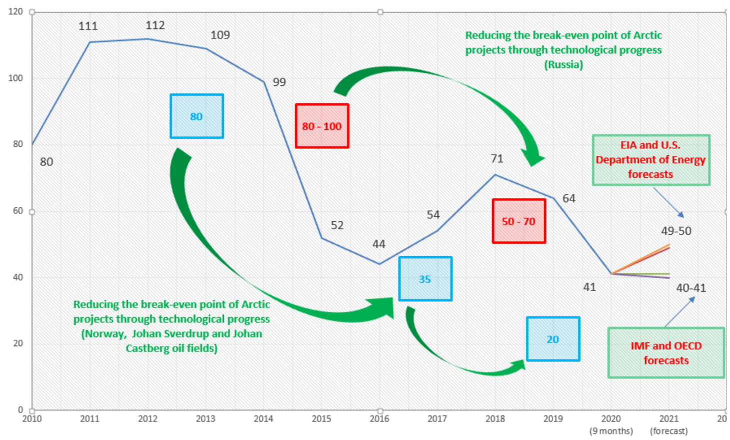

Figure 2. Changes in oil prices and the break-even point of offshore oil and gas projects in the Arctic. Source: Created by the authors, data from [6,43,49,55–62].

According to the latest estimates by the Ministry of Energy of Russia, the break-even point of oil and gas offshore projects in the Russian Arctic is around $50–70, while the Norwegian company Equinor (formerly known as Statoil) claims that the break-even point for the development of the Johan Sverdrup field is less than $20 per barrel. In addition, after reaching the first-phase plateau (summer 2020), operating costs are expected to be below $2 per barrel [57]. Norway has made great strides in the development of Arctic hydrocarbons, demonstrating record low costs of offshore oil production. This is a result of technological advances and managerial efficiency.

In general, for Arctic offshore hydrocarbon projects to be successful, there should be either high oil prices, which are difficult to predict and not possible to control, or breakthrough technologies and innovative solutions that could provide a significant reduction in operating costs. The latter is an area whose development can open up new opportunities for offshore oil production. At the same time, any technological improvements require special approaches to strategic development and management, especially in times of global disturbances and high uncertainty.

3.2. Global Trends and Challenges for the Strategic Development of Oil and Gas Companies

A world of resource abundance is leading to a revaluation and gradual decline in oil prices as well as a focus on cost, efficiency, and speed [40]. The energy sector is characterized by intense competition (for markets and end users), a high degree of uncertainty and the speed of development of new technologies, and an orientation toward green growth [63].

The system of factors that influences both global energy markets and the operations of oil and gas companies is becoming more and more complex. It consists of political, economic, technological, social, and environmental factors that are global in their nature, many of which are unpredictable.

The business models of large oil and gas companies are vertically integrated [37]. For quite a long time, this model ensured the stability of companies in the sector. However, today, when the nature and speed of changes in the external environment have changed significantly, traditional approaches to maintaining sustainability (vertical integration, ensuring access to raw materials, diversifying activities and sales, a developed infrastructure and logistics system, etc.) are undergoing a transformation. Today, the exploration capabilities of oil and gas companies are not their distinguishing feature, megaprojects are not the only way to ensure strategic growth, and market opportunities can only be cost-effective for the industry leaders [40].

A number of global trends influence the activities of oil and gas companies and the energy sector as a whole. Figure 3 shows how global megatrends can be divided into groups such as Society and Ecology, Technologies, and Business Environment; together they create a set of common challenges for oil and gas companies, the systems, and directions of their strategic development. Table A1 provides a more detailed description of the key global trends, challenges, and ways that oil and gas companies can adapt.

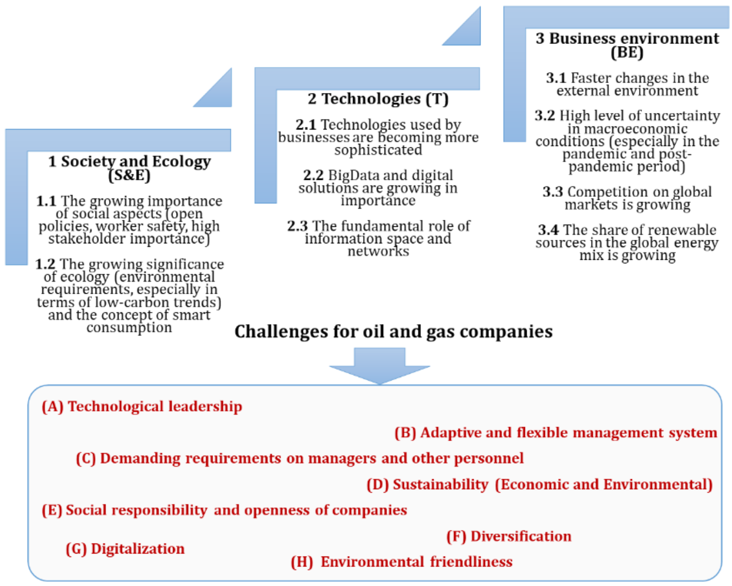

Figure 3. Global trends and challenges for the strategic development of oil and gas companies. Source: Created by the authors, data from [14,21,40,64–72].

Deep tech innovations are putting an end to old work practices and make it possible to gradually improve productivity and, as a result, efficiency [40]. The depletion of conventional oil and gas reserves forces companies to develop complicated oil and gas projects (unconventional oil and gas, offshore, and shale projects), which generally require higher CAPEX and OPEX. All this creates new challenges for oil and gas companies and makes the sector more and more technologically sophisticated. Oil and gas businesses can no longer ensure their sustainability by relying on easy-to-recover resources, and technology is playing an ever-increasing role at all stages of the production process.

The high volatility of oil prices leads to adjustments in the companies' business plans and changes in their portfolios. As the oil and gas industry is becoming less economically sustainable, projects that heavily depend on oil prices become frozen or dismissed.

An important response made by oil and gas companies to the price volatility and uncertainty of the external environment is diversification, which manifests itself in the development of the value chain in the gas segment through the implementation of LNG (liquefied natural gas) projects, building up renewable energy assets, developing petrochemical and gas processing businesses, investing in the environment, electric vehicles, etc. At the same time, conventional, deepwater, unconventional, renewable, and other assets require separate approaches to management as well as different strategic business units (SBUs) and business models [40] that cannot operate based on the same principles or one set of technology.

Industry 4.0 brings to the fore the digitalization of industrial, organizational, and management processes [69]. Many oil and gas companies have begun to take advantage of digitalization, the Internet of Things, and robotics. These new technologies have enabled oil and gas companies to significantly reduce production costs and increase sales [46], and they have also changed approaches to sustainable development in the oil and gas industry. They are becoming an indispensable component of sustainable development. This imposes requirements not only on the need to develop technologies and to build up digital competencies of oil and gas companies, but also on their labor market and personnel policies. Programmers have become the most in demand professionals; automation and digitalization make workers redundant, and the remaining positions imply close man–machine interaction. In the long-term, there will be new job types and opportunity profiles [40].

The environmental factor largely determines the vector of sustainability in oil and gas and is bound to continue to do so in the future. The fight against anthropogenic CO_2 emissions has made the global community and oil and gas businesses pay more attention to renewables and the development of green initiatives within the company.

Approaches to social sustainability in the oil and gas industry are also being transformed; an increasing emphasis that businesses place on society is being expressed through social and environmental activities.

In this context, oil and gas companies implement a variety of innovative strategies, for instance, the open innovation model, which could support dealing with the industry's challenges (mostly social and environmental pressure) [73].

In general, the energy sector is undergoing a transformation due to factors such as low-carbon initiatives growing in importance, the desire to reduce the companies' dependence on the oil and gas market, and the desire to use opportunities provided by digitalization. The first aspect threatens the leading position of oil as an energy resource. For instance, fusion energy as well as other energy sources could successfully address long-term energy requirements and the issue of climate change [25,74].

Oil still accounts for the biggest share in the global energy mix (about 33% in 2019) [49]. However, as experts predict, this share will steadily decline. According to the IFA estimates [75], global oil demand will hit a plateau around 2030; it will grow until 2025, slowing down to a minimum thereafter. According to BP, which predicts two energy mix scenarios due to the transition to a low-carbon energy system, renewable energy sources and natural gas will have become more important than oil and coal by 2040, with oil consumption shrinking [21]. According to one of the considered scenarios (the Rapid Transition Scenario), BP estimates that the share of oil in the energy mix will be 24% in 2030 and 17% in 2040 [21].

All the issues discussed above lead to the transformation of sustainable development parameters in the industry. Global trends and the challenges of the last decades highlight that economic aspects in the context of sustainable development are not always a priority and often yield to environmental, social, and technological ones. Energy resources are becoming more and more an instrument of geopolitics. The concept of energy sector sustainability that is based purely on market aspects is being disrupted, and non-economic forces are emerging. The role of non-market actors is growing, and some of them impose innovations on companies, requiring costly changes [76].

The main problem is the need to develop and successfully run businesses in the context of high unpredictability and a surprising business environment. I. Ansoff introduced these categories as well as the concept of environmental turbulence in the middle of the last century [77,78]. I. Ansoff introduced and substantiated five levels of environmental turbulence (from 1 to 5). He presented the matching of environmental turbulence, strategic aggressiveness, and responsiveness of the organization's capability [32,78,79]. As the turbulence of the external environment increases, the management of a company must master the science of fast and effective change [31]. The researcher argued that the strategic success of a company is ensured only if the development level of the strategic management system (strategy, top management) corresponds to the level of turbulence in the external environment.

The energy sector is currently in the process of transformation, and it ranks 5 on the turbulence scale, which indicates high complexity, high speed of change, and unpredictability.

All these aspects determine the requirements on strategic management systems and management personnel. Management approaches and frameworks need to be consistent with the new reality that dominates the energy sector. The next section discusses the key aspects of the transformation of the strategic management and planning systems of oil and gas companies that could significantly contribute to the success of the companies' operations and Arctic offshore hydrocarbon projects in a new reality.

3.3. Transformation of Strategic Management and Planning Systems of Oil and Gas Companies: Key Aspects

The strategic management of oil and gas companies and their SBUs in the context discussed above should be based on a set of new principles including those that could increase the company's flexibility and adaptability in achieving its strategic goals and help to develop management creativity.

A number of strategic management functions are generally accepted including basic functions such as strategic analysis, strategic planning, and forecasting. New requirements are being imposed on them.

As for strategic analysis techniques, together with widely used and debatable methods such as PEST analysis, SWOT framework [34], etc., a special role is assigned to instruments for analyzing the phenomena and processes that dominate the energy sector, measuring its uncertainty, predicting the future (for instance, event analysis), and analyzing business sustainability in a highly volatile environment. These instruments can include the following: an analysis of a company's core competencies based on the concept introduced by C.K. Prahalad and G. Hamel that defines a core competence as the "most powerful way to prevail" [80]; a business model analysis focusing on the assessment of the shares of various SBUs in the company portfolio (oil exploration and production, petrochemistry and gas processing, renewable energy, other types of business); and an analysis of the value chain [33] of an oil and gas company as a "collection of activities that are performed by a company to create value for its customers". The latter provides a comprehensive review of the value creation for all processes and products produced in different businesses.

Within the framework of forecasting, in addition to forecasting the development of markets and technologies, it is necessary to assess global trends such as climate change and the growth in the use of non-fossil fuels in the global energy mix. A special role is played by forecasting the development of the range of products produced by petrochemistry and gas processing as well as the beneficial use of industrial waste including an increase in the value of technogenic CO_2 [81]. Complex forecasting models (those combining social, ecological, technological, and other factors and indicators) are of crucial importance.

Strategic planning forms a combination of programs and projects that should be multiple and adaptive. The strategic planning systems of oil and gas companies should also be continuous, but there may be no clear time cycles. The strategic plan that is created should be able to be adjusted outside the planning cycles. In oil and gas companies, strategic planning is mostly a calendar-driven ritual, and the planning process is generally elitist, "harnessing only a small proportion of an organization's creative potential" [82]. It is important to use benchmarking practices.

In general, the strategic management of SBUs for offshore hydrocarbon production in the Arctic is a complex process where interaction with the external environment plays a crucial role, and the rate at which complex industrial systems for offshore hydrocarbon production are being developed is growing.

A conceptual vision of the basic transformation of strategic management systems is presented in Figure 4.

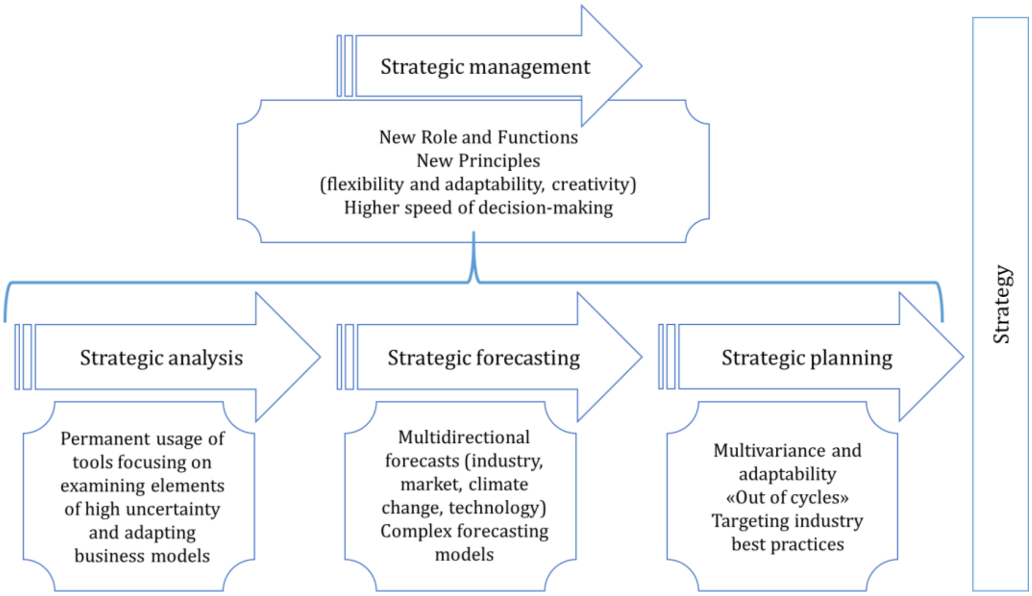

Figure 4. A conceptual vision of the basic transformation of strategic management systems of oil and gas companies. Source: Created by the authors.

Strategic control as the final stage of the strategic management process is also very important. This stage usually involves the use of balanced scorecards and their derivatives (for instance, the approach proposed by Kaplan and Norton) [83]. A balanced scorecard for assessing strategy efficiency is developed, as a rule, depending on the strategic and tactical goals. In the strategic management systems of oil and gas companies and their offshore assets, balanced scorecards could be specific and they should certainly correlate with sustainable development goals (including those associated with environmental and social sustainability) and include investment and organizational performance, the parameters of improving employee competencies, etc. In addition, the strategic control system should include strategic auditing. With the use of information systems, it is necessary to measure the progress of offshore projects and to assess both managerial solutions and the quality of business and functional strategies that have been developed.

Thus, the reaction in the strategic management system should be faster than it used to be. The strategic management and planning system should contribute to the survival and economic development of complex SBUs in the Arctic, ensuring their ecological balance and social orientation in a highly unpredictable environment. In the near future, sustainability will be more present and obligatory [84,85].

The transformation of the requirements on the strategic management system in the context of global challenges, high uncertainty, and global shocks caused by the pandemic are shown in Figure 5.

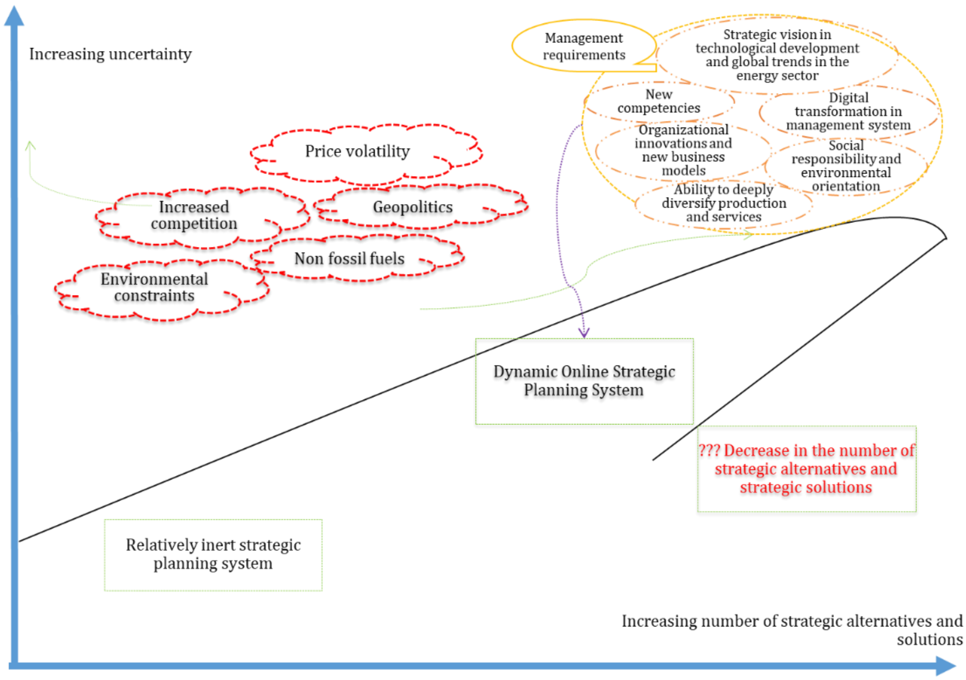

Figure 5. Changes in strategic management requirements under the transformation of the energy sector and global disturbances. Source: Created by the authors.

As noted above, the role of low-carbon initiatives is growing, and the share of fossil fuels may significantly decrease in the long run. The growing role of CO_2 mitigation options including the case of Arctic hydrocarbon projects will force oil and gas companies to extract/capture CO_2 and perform carbon dioxide storage (CCS) or usage (CCUS) operations, which will require expensive technological and engineering solutions. These factors, along with geopolitical issues, price volatility, tough competition, and a decrease in the cost of renewable energy, contribute to the growth in uncertainty in energy markets (Figure 5, axis Y).

In this regard, the requirements on the strategic management systems of oil and gas companies are increasing, especially in SBUs involved in offshore hydrocarbon production in the Arctic. The uniqueness of technological and organizational solutions as well as their inconvertibility, requires special competencies from managers and specialists working for oil and gas companies. The role of the system integrator is of critical importance. Strategic management and planning should contribute to the creation and development of new competencies and business practices. Digitalization of both production operations and the decision-making process is one of the requirements imposed on today's strategic management systems. A strategic vision of modern trends in ensuring technological leadership including that in the area of environmental technologies and the diversification of production and products is also in the focus of strategic management. In addition, the importance of social responsibility of an oil and gas company should not be overlooked, especially in terms of preserving the Arctic's ecosystems and biodiversity and the traditional way of life of locals living in the coastal regions of the Arctic.

We can assume that in the pandemic and post-pandemic periods, uncertainty will grow even more, and there is a need to increase the number of strategic alternatives developed by managers at oil and gas companies. The uncertainty and dynamism of the business environment raise the question of whether the strategic management system will return to the least number of strategic alternatives and solutions (Figure 5, axis X). The post-pandemic period is likely to be characterized by long-term low prices for hydrocarbons, which are currently below the break-even point of Russian Arctic offshore projects, and a decrease in demand for fossil fuels (due to the economic crisis and low-carbon trends). The influence of the latter may increase due to J. Biden's victory in the U.S. presidential election, who promised to reenter the U.S. into the Paris Agreement and invest trillions of dollars in green energy [86]. With such prospects, oil and gas companies need to diversify their portfolios by focusing on the downstream sector, petrochemistry products, and gas processing products.

Based on the above, we present the key principles of strategic management and planning (Table 2) that could contribute to the oil and gas companies' successful operation and implementation of complex offshore hydrocarbon projects in the Arctic against global disturbances (i.e., a range of complex factors discussed above ("a new reality") including pandemic and post-pandemic trends). We can say that being put together, these aspects form an environment characterized by global disturbances.

Table 2. Changes in the principles of the strategic management and planning of oil and gas companies in the context of global disturbances.

Principles	"A new reality": the era of competition, globalization, and high uncertainty	"A new reality" + pandemic and post-pandemic scenarios = global disturbances
Authority and responsibility	Greater independence of project managers	Limiting the number of decision makers
Adaptability	High adaptability of the strategic planning system and integration of programs and projects into current plans	Cyclicity is not a basic characteristic. Changes in strategic decisions in one planning cycle. Planning "online"
Scenario-building	Baseline scenario and several development alternatives	Simulating a large number of scenarios with detailed risk descriptions
Risk mitigation	Risk assessment and management	Strengthening the risk management component: mandatory creation of insurance funds and capital
Efficiency	Commercial (financial), social, environmental	Growth in the role of environmental and social efficiency. Competence and technological efficiency
Focus on the environment	Environmental risk management is required	More stringent requirements concerning environmental safety. The almost complete exclusion of possible environmental damage
Focus on creativity	Ability to make non-standard decisions and think out of the box in the context of high uncertainty	Requirements for a decision maker to be a "system integrator" with an ability to solve different tasks through interdisciplinary competencies
Focus on digitalization	Digital transformation of management and planning systems	Faster digital transformation with the creation of digital managerial competencies

Source: Created by the authors with the use of [36,82,87–89].

We highlight the principles of authority and responsibility, adaptability, scenario-building, risk mitigation, and efficiency as well as the principles of focusing on environment, creativity, and digitalization. A number of principles are widely known in strategic management and planning systems. However, some principles of strategic management and planning in the Arctic SBUs of oil and gas companies are becoming crucial for the implementation of complex programs and projects in the Arctic, for example, the focus on environment and digitalization. Such principles are fundamentally new for industrial companies. Traditional principles are undergoing a transformation. For example, speaking of efficiency, we cannot focus only on economic efficiency because social, environmental, and technological aspects of efficiency are also becoming very important. In the context of pandemic and post-pandemic scenarios, the characteristics of the new principles that have been developed over the past few years are also being somewhat transformed. The planning cycle is becoming more dynamic, the interests of stakeholders should be taken into account more fully, and the role of risk insurance is growing. Moreover, the management of oil and gas companies has no room for errors in ensuring environmental safety in offshore hydrocarbon production. It is also necessary to make jobs in the Arctic attractive [90].

4. Discussion

Currently, the world as a whole is changing due to the COVID-19 pandemic [84] and other factors that have been discussed. We admit that the development of offshore hydrocarbon resources in the Arctic may be viewed as being against the principles of sustainable development. Such projects pose a high risk to the environment as they may cause biodiversity disruption. If an oil spill occurs in the Arctic, eliminating the consequences of such an accident is very difficult due to the polar night, low temperatures, underdeveloped infrastructure, and the lack of reliable technological solutions. Therefore, strategic solutions for the development of offshore hydrocarbon resources in the Arctic should be aimed at ensuring environmental safety.

The development of underwater drilling and hydrocarbon production technologies is of great importance, therefore, it is necessary to upgrade offshore drilling equipment and improve the reliability of oil spill response technologies. The quality and accuracy of exploration equipment and technologies including seismoacoustic and seismic R&D as well as 3D exploration with digital processing and integrated data interpretation should meet all modern requirements.

Industry 4.0 technologies are becoming more and more important since they can facilitate sustainable practices [84] and could play a special role in strategic management. New digital technologies, combined with datasets, can transform field operations, making strategic decisions faster, more efficient, and better. The ability to collect and interpret data and then take effective action while minimizing risks to employees and the environment will be at the core of strategic management in the near future.

At the same time, the strategic management and planning system should provide a clear rationale for Arctic projects. The strategic management system should recognize the existing constraints and envision difficulties in implementing strategic Arctic plans. In this light, strategic alternatives connected with the development of conventional or unconventional oil reserves on land could be preferable.

Implementing offshore hydrocarbon projects will allow for new technological solutions to be tested and new competencies to be acquired. However, the experience acquired and the unique competencies developed could be used on a large scale only if there is a demand, which may be low or completely absent. We assume that low oil prices and the growing interest in renewable energy will bar companies from implementing Arctic projects on a large scale (i.e., no more than one or two projects may be executed). In the end, it will not let oil and gas companies use the unique competencies that they have acquired. This is also an issue for the strategic management and planning system to solve as the company's R&D efforts can be directed toward other promising projects (for instance, diversification of downstream operations).

The principles of strategic management aimed at enhancing the role of social and environmental responsibility can also become an obstacle to offshore oil and gas production from an economic point of view. Compliance with strict environmental standards and high social responsibility to workers and local communities entails serious additional CAPEX and OPEX; the industry needs to respond to these environmental and social concerns in an economic and sustainable way [73].

We can assume that financial efficiency should not be the main point and that the principles of sustainable development are very important. We can even assume that offshore oil and gas production is not only a business, but also the opportunity to develop unique competencies and create an image of a responsible and advanced company. However, in any event, oil and gas companies (like everyone else) operate following the principle of economic pragmatism. The development of projects where there may be a lower degree of stakeholder influence, fewer restrictions, and greater financial efficiency is an alternative that oil and gas companies still have, taking into account the low oil recovery rate in Russia and the great opportunities to improve the economic indicators of such projects. In general, the economic vector of offshore oil and gas production in the Arctic should be directed at improving industrial management, developing unmanned systems, automating all operations, and reducing semi-fixed costs as much as possible. In such a way, economic results can bring the break-even point of offshore production down, which can be observed in Norway.

We highlight the creativity and the ability to think using interdisciplinary knowledge as qualities characterizing the manager as a "system integrator". It is also necessary to develop cross-cultural competencies in modern management. Managers need to learn from the experience of national and transnational management systems, and the managerial experience should be used properly in Arctic SBUs. This is the area that we would like to study in our further research.

5. Conclusions

To summarize the research, we would like to underline the following points:

1. An event analysis was conducted to study changes in oil prices. Additionally, global challenges and megatrends in the energy sector were analyzed that create a new reality to which oil and gas companies need to adapt. The oil and gas sector including offshore production in the Arctic is characterized by increasing uncertainty accompanied by a variety of risks, among which are environmental, technological, and investment ones.
2. Management requirements in the framework of strategic management systems were identified. These systems should be aimed at developing new business models, competencies, and the ability to strategically predict technological and organizational changes. They should also be highly responsible in terms of social and environmental challenges.
3. The principles of strategic management for the development of offshore projects in the Arctic were improved. They take into account the need to face the global challenges of recent years including pandemic and post-pandemic trends. In developing strategic plans, it is necessary to focus on a large number of scenarios, develop adaptive mechanisms, and ensure that the company's operations comply with stringent environmental regulations.
4. The focus on creativity is an important point in today's strategic management systems. In the context of growing uncertainty and an ever-increasing number of extraordinary situations, it is vital for businesses to take a creatively different approach to management. In offshore oil and gas production, a focus should be made on optimizing labor utilization on-site, which strengthens the role of digital technologies and smart systems (both technological and managerial ones).

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Appendix A

Table A1. Global trends, challenges, and approaches that oil and gas companies can take to adapt to a new reality.

Sphere–A Global Trend–Key Challenges	Description	Challenges for Oil and Gas Companies	Companies' Adaptation Tools
1 S&E–1.1–E, D	Growing importance of social factors in the company's activities. A higher degree of the company's responsibility to its employees and society as a whole	- Publicity - Taking into account the interests of a wide range of stakeholders - Ensuring smooth production and its safety - Ensuring favorable working conditions - Ensuring a high quality of life for the people in the regions where the company operates - Participation in the social development of the regions	- Implementing the principles of sustainable development (social, economic, and environmental aspects) - Implementing internal and external social policies - Improving the system of interaction between the company and stakeholders - Developing publicity strategies; image making - Digitalization aimed at ensuring safety at work and environmental safety - Implementing the principles of a circular economy (circular models)
1 S&E–1.2–H, D	Growing public concern about the environment. A higher degree of the company's responsibility to society and the environment	- Ensuring a minimum level of environmental impact - Compliance with stringent environmental regulations imposed on both production processes and end products	
2 T–2.1–A, C	Growing technological sophistication of businesses against the background of the gradual depletion of conventional oil and gas reserves; the need to implement high-tech projects; more stringent environmental regulations that both production processes and end products have to comply with	- Technological leadership (by technology, equipment, and competencies) - The need to use more advanced technologies for the exploration, production, transportation, and processing of hydrocarbons	- Implementing various strategies aimed at technological development (co-financing R&D, creating partnerships for complex projects, using the model of "open innovations", etc.) - Developing competencies in technological and digital leadership - Fostering intrapreneurship - Implementing various digitalization strategies (integration with IT companies, creation of the company's own IT departments, improving personnel policies) - Studying the value chain and developing a list of critical digital technologies "Industry 4.0"
2 T–2.2–G, C	Rapid development of technologies for obtaining, storing, processing, and using data, which provides the opportunity to improve production efficiency and upgrade production and management processes	- Digital transformation - Improving the company's production and managerial performance through digitalization	
2 T–2.3–D, E	Rapid development and improvement of Internet and cloud technologies and the growing popularity of social networks, which makes it necessary to change the conduct of business principles	- Meeting society's environmental, ethical, and social needs - The growing role of society's "requests for transparency" - Creating the company's informational platform	

Table A1. *Cont.*

<table>
<thead>
<tr><th>Sphere–A Global Trend–Key Challenges</th><th>Description</th><th>Challenges for Oil and Gas Companies</th><th>Companies' Adaptation Tools</th></tr>
</thead>
<tbody>
<tr><td>3 BE–3.1–B, C, D, F</td><td>A volatile and, as a result, unpredictable external environment with ongoing significant changes in prices, markets, and also technological, social, environmental, and regulatory factors</td><td rowspan="2">- Business sustainability under any scenario (including low prices for oil)
- A flexible (adaptive) strategic management system
- A controllable degree of dependence on oil markets</td><td rowspan="4">- Diversification (reorientation to the production of products with high added value (oil and gas processing products) and development of new low-carbon businesses, products, and services that complement current activities)
- Improving the operational efficiency of the business (reducing costs and improving productivity)
- Digitalization
- Developing a set of competitive advantages and key competencies</td></tr>
<tr><td>3 BE–3.2–B, C, D, F</td><td>A high degree of uncertainty regarding key macroeconomic parameters, especially oil prices during the pandemic</td></tr>
<tr><td>3 BE–3.3–D, F</td><td>Rivalry between companies for limited areas (markets, consumers, resources) and leadership (technological), which leads to increased competition between oil and gas companies at all stages, from licensing to selling products</td><td>- Business sustainability in a highly competitive environment
- Competent leadership</td></tr>
<tr><td>3 BE–3.4–F, D</td><td>A growing role of renewable energy sources in the global energy mix due to low-carbon policies becoming mainstream</td><td>- Business sustainability in the context of a possible decline in the share of oil in the global energy mix
- Compliance with the principles of the low-carbon agenda</td></tr>
</tbody>
</table>

Source: Created by the authors with the use of [14,21,40,64–71].

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Approaches to Assessing the Strategic Sustainability of High-Risk Offshore Oil and Gas Projects

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Abstract: In the face of today's global challenges, oil and gas companies must define long-term priorities and opportunities in implementing complex Arctic offshore projects, taking into account environmental, economic, technological and social aspects. In this regard, ensuring strategic sustainability is the basis for long-term development. The aim of the study is to analyze existing approaches to the concept of "strategic sustainability" of an offshore Arctic oil and gas project and to develop a methodological approach to assessing the strategic sustainability of offshore oil and gas projects. In the theoretical part of the study, the approaches to defining strategic sustainability were reviewed, and their classification was completed, and the most appropriate definition of strategic sustainability for an offshore oil and gas project was chosen. The method of hierarchy analysis was used for strategic sustainability assessment. Specific criteria have been proposed to reflect the technical, geological, investment, social and environmental characteristics important to the offshore oil and gas project. The strategic sustainability of 5 offshore oil and gas projects was analyzed using an expert survey as part of the hierarchy analysis method. Recommendations were made on the development of an offshore project management system to facilitate the emergence of new criteria and improve the quality of the strategic sustainability assessment of offshore projects in the Arctic.

Keywords: offshore; Arctic; hydrocarbon resources; oil and gas projects; strategic sustainability; investment; technological; geological; environmental and social criteria

1. Introduction

Over the last decade, the global trend in the majority of oil and gas producing countries has been to reduce oil and gas production in traditional oil and gas production centers. At the same time, the Arctic continental shelf is one of the most attractive and promising areas in terms of hydrocarbon resource potential. According to preliminary estimates, up to 25% of the world's hydrocarbon reserves are concentrated in the Arctic, guaranteeing energy security for many European countries and the world for decades to come [1]. The estimated hydrocarbon potential of the Russian Arctic shelf for recoverable reserves is 9579.3 million tons of fuel equivalent [2,3]. For many decades, Russia has been actively developing the mineral and raw material potential of the Arctic [4,5].

The Russian Federation is one of the largest exporters of fuel and energy raw materials under the existing international division of labor system. The competitive advantage achieved in Russia's oil and gas sector on the global energy market can ensure the stable development of the national economy and social sphere and the formation and replenishment of budgets at all levels. Russia's Energy Strategy for the period until 2035 determines the need to bring annual oil production to 490–550 million tons. Achievement of the planned production levels is possible with oil reserves replacement in the amount of more than 13–15 billion tons [6].

Many specialists and experts believe that the key strategic objective for the long-term sustainable development of the oil and gas industry is the balanced development of the Arctic hydrocarbon potential, including, above all, the environmentally safe development of offshore fields [7–11]. The government and operators of Arctic oil and gas projects are faced with new organizational and managerial tasks, the solution of which will improve the sustainability of offshore hydrocarbon development in the Arctic shelf, ensuring the economic efficiency of all project participants, taking into account social factors in the development of Arctic territories, the environmental balance and technological development [12–16].

For the successful development and sustainable functioning of the oil and gas industry in the Arctic zone, a set of tasks must be successfully completed, which include scientific, technological, infrastructural, social and investment attraction tasks in this sector. Difficult climatic conditions, high capital intensity, irreversible technological and managerial mistakes that lead to environmental disasters highlight the high risks of offshore oil and gas projects. It is also necessary to take into account the long-term nature of such projects and their strategic orientation, i.e., such projects require serious costs and involve irreversible management decisions in the areas of economics, technology and logistics, together with constantly arising geopolitical factors [17–19]. The assessment of offshore Arctic oil and gas projects in Russia practically does not take into account the carbon intensity factor of newly established production facilities. Global low-carbon development trends and the fight against anthropogenic CO_2 emissions [20,21], along with the growing share of renewable energy and the global players' plans to reduce oil production on the world energy market, are precisely the challenges that Russian companies' management must take into account when determining the prospects for developing the Arctic shelf.

The authors of this study, however, believe that the development of Arctic marine hydrocarbon resources is a major challenge that threatens natural systems. It may be better to develop fields on land and to increase the oil supply of old fields, where technologies have been tested, including those for environmental protection. However, if the company begins to implement offshore projects in the Arctic, environmental and safety issues will be fundamental. The start of such projects must therefore be accompanied by a detailed sustainability assessment, with priority consideration of the environmental factor and of all impacts on local communities.

Ensuring the strategic sustainability of oil and gas projects is directly linked to the specifics of the oil and gas industry, particularly offshore oil and gas production in the Arctic, and to global processes, particularly the consequences of the pandemic and the ability of oil and gas companies to develop in the post-pandemic period.

The profitability of oil and gas production is determined by fluctuating demand in global markets, which in turn are affected by the global coronavirus pandemic crisis. A significant drop in global hydrocarbon prices due to a fall in global production during the pandemic, increased use of alternative energy sources and opportunities to increase unconventional hydrocarbon production may lead to the freezing of investment activities and the closure or indefinite postponement of oil and gas projects [22,23].

Given the high volatility of oil prices and the loss of profit for oil and gas companies, as well as government revenues, there may be a serious decline in exploration work aimed at increasing hydrocarbon reserves. In other words, the industry may remain with a low oil and gas reserve replacement rate [23].

Most of the Russia's new fields (Arctic shelf, Eastern Siberia, Far East) are located far away from transport and port infrastructure and consumers, so the profitability of their production, especially with small reserves, can be marginal to profitability or negative. However, oil in new fields often has the worst chemical composition, particularly in terms of sulfur content and density. The decline in the quality of the resource base is a major challenge for the Russian oil and gas sector and its sustainable development, along with the coronavirus pandemic and EU and US sanctions [23].

In connection with the above, the authors of the article can state that approaches to assessing the strategic sustainability of high-risk Arctic oil and gas projects are a relevant area of study.

The purpose of the study is to analyze the existing approaches to the concept of "strategic sustainability" of an offshore Arctic oil and gas project and to identify a set of indicators required for strategic sustainability assessment, as well as to propose a methodological approach to assessing the strategic sustainability of offshore oil and gas projects and provide recommendations on the development of a strategic sustainability assessment system for offshore oil and gas projects.

The following research questions are raised in the article:

- What is meant by the strategic sustainability of an offshore oil and gas project in the Arctic?
- What are the criteria for assessing offshore oil and gas projects, taking into account their specific features, global energy sector trends and the risks associated with these projects?
- What can be suggested to improve the strategic sustainability assessment of an offshore oil and gas project?

The structure of the article is the following:

- Study of theoretical approaches to determining the sustainability and strategic sustainability of complex industrial systems and offshore oil and gas projects;
- Identification of key risks in offshore projects;
- Identification of specific criteria for assessing the strategic sustainability of the offshore oil and gas project;
- Identification of suitable methodological tools for assessing the strategic sustainability of offshore oil and gas projects in the Arctic;
- Assessing the strategic sustainability of existing offshore projects in the Russian Arctic shelf using expert surveys;
- Recommendations on developing a system of strategic sustainability assessment indicators.

Therefore, first, we would like to look at existing theoretical approaches to defining the strategic sustainability of offshore oil and gas projects in the Arctic.

2. The Problem of Strategic Sustainability of Offshore Oil and Gas Projects in the Arctic

Despite an extensive list of studies on the strategic sustainability of industrial systems and projects, there is currently no generally accepted methodology for assessing it. This is particularly true for Arctic oil and gas development projects, which are highly risky and have a strong specific nature. In general, a project is a set of processes aimed at creating a unique product, service or result that meets specific requirements defined in advance, including time, cost and scope limits [24–27]. The Offshore Oil and Gas Project is the creation of a unique industrial system for the production of hydrocarbons within a certain budget in order to achieve the planned result.

In oil and gas companies, projects are usually divided into two categories: investment projects—projects that involve capital expenditure for the purpose of making a profit and/or achieving other beneficial effects; operational projects—other projects involving non-capital expenditure.

Project management is an important process that ensures the reasonable and efficient use of funds, including investment resources, for the development of enterprises in accordance with their strategic and annual plans. Project management is linked to the strategy, accompanied by a stated mission and vision, as well as strategic goals and objectives, in order to balance the use of resources in carrying out strategic and operational activities. That is, any oil and gas project, in addition to economic (financial) sustainability, must also have strategic sustainability.

The concept of sustainability is not uniquely defined because it is widely used in different areas with different meanings and implications.

2.1. Definition of Sustainability

Let us consider the approaches of various authors to the definition of sustainability at the project level (business entity).

According to Teplova [28], "sustainability of an investment project is a characteristic of a project that shows that it remains effective when the conditions for its implementation change".

The Big Economic Dictionary, edited by Azriliyan, A.N. [29], gives the following definition: "sustainability is firmness, constancy and not subject to the risk of loss or damage".

According to Lopatnikov [30] he stability of a system is the ability of a dynamic system to maintain movements along its intended trajectory (maintain its intended mode of operation) despite disturbances affecting it.

According to Altshuler [31] sustainability is a constant response to changes in the external environment, provided that the company's income and output are managed in line with market requirements.

Finally, Manitskaya, L.N. in her work [32] declares that sustainability is the ability of the system to function effectively in the face of external influences and internal disturbances.

As we can see, a common concept in the authors' definitions of "project sustainability" is the ability of a project to function effectively in a fluid environment with high uncertainty and to return to a balanced state more quickly. Such definitions are more suited to the concept of sustainability. In our study, we do not consider it appropriate to use these definitions, which are only partially appropriate for oil and gas projects. The above definitions do not reflect the specifics of offshore oil and gas projects where companies operate in a fragile environment, global trends in the need to combat greenhouse gas emissions and high social responsibility.

It is very important to clearly identify the definitions of "sustainability" in the global context, because this context reflects the need to assess the sustainability of the offshore oil and gas project from a social and environmental perspective. A large number of definitions were proposed after the well-known Brundtland report "Our Common Future" was published [33]. The main idea of sustainable development outlined in this report is that our planet's resources are limited and that, given current consumption patterns, there are a number of risks and disasters ahead of us that are linked to the negligence of people towards our planet. Sustainability generally refers to economic, environmental or social sustainability [34]. On the contrary, development without environmental, social and economic sustainability will lead to a collapse of the economy, society and the environment [35].

Economic sustainability refers mainly to economic growth and the various practices that support it in the long term. The quantitative definition of economic sustainability refers only to economic growth, which is defined as the ability of an economy to maintain a certain level of economic production. In this case, sustainable development is confused with economic growth [36]. An increasing number of scientists are now expressing concern that current economic growth can no longer be sustained without damaging our planet [37]. Economic growth cannot be sustainable if natural resources are used without restrictions or if society continues to depend on economic activities such as the extraction of natural resources, which were the driving force behind economic growth in the past [38]. There are also more complete definitions of economic sustainability. For example, such definitions include qualitative growth that is not associated with increased consumption of natural resources. The concept of fair economic sustainability speaks to the fair distribution of the benefits of economic growth in society [39].

Environmental sustainability is defined as respect for nature in order to conserve natural resources and avoid deterioration of soil, air, water, biodiversity, etc. According to the environmental component of sustainable development, the needs of the present generation must be met without compromising the needs of the future generation, which means that future generations will have the same quality of water, air, soil and biological diversity. The term "environmental sustainability" is closely linked to the term "sustainability", which sees the entire earth as a system that must preserve its integrity and return to a state of equilibrium after various shocks [40]. The goal of environmental sustainability is to maintain the balance of our planet within its boundaries, such as climate change, biodiversity loss or changes in the global nitrogen cycle [41]. The issues of climate change and CO_2 mitigation options are of great importance, and it must be assumed that global processes in the global economy dictate the need to increase energy efficiency in all sectors, to replace coal and oil generation with natural gas; to actively use solar, wind, geothermal and hydro power and to introduce CO_2 sequestration technologies on a large scale. Of course, in order to assess strategic sustainability, it is advisable to take into account the challenges for conventional energy (fossil fuels) that exist in the context of society's struggle against global climate change [42,43].

The existing definition of environmental sustainability is closely linked to Environmental Impact Assessment (EIA), which is one of the tools for implementing environmental sustainability. The purpose of the EIA is to reduce or prevent negative environmental impacts of infrastructure projects, including oil and gas projects [44]. When planning infrastructure projects in the Arctic, the purpose of the EIA procedures is to protect the fragile nature of the Arctic region, which is also a habitat for indigenous peoples in the region [45]. For example, reindeer husbandry is one of the most important indigenous and traditional livelihoods in the circumpolar Arctic and the Barents region [46], and this depends to a large extent on the well-being of the environment. The purpose of the EIA is therefore not only to protect the environment but also to reduce the risks associated with the development of industrial infrastructure, such as the development of an oil and gas field in the Arctic and changes in land use [47,48].

Existing definitions of social sustainability are linked to the impact that policies or infrastructure projects have on the local community, in the regions where the projects are planned. Social sustainability is not always given the right emphasis in the context of sustainable development [49]. In addition, social sustainability was often given the lowest priority in international policy development or major international projects [50]. More and more attention is now being paid to this term. The development of projects contributes to the growth of jobs, the professional skills of employees and their competences. In addition, the social aspect of sustainability is expressed through the inclusion of public opinion in the implementation of major industrial and infrastructure projects, including projects related to the development of hydrocarbon deposits, and the need to combat public protests, as well as the development of policy decisions on the construction of industrial facilities and infrastructure that are based on principles of fairness. Equity principles include such factors as the distribution of the results of decision-making processes and procedural fairness, which means how different social groups are involved in decision-making processes. In response to this need, a number of international organizations have developed social impact assessment (SIA) procedures [51,52]. SIAs were first introduced in the US and then widely implemented in a number of other regions and countries with multilateral donor organizations such as the World Bank [53], which plays an important role in their implementation [54]. This understanding of social sustainability goes beyond the so-called "not in my backyard yard" concept. (NIMBY) or various types of "decide-announce-defend" models [55,56].

The concept of social justice and social equity was frequently discussed in various scientific works. It was also described as social, distributive or output justice; fairness over distribution and access to resources or equality in various conditions which are important for the modern lifestyle. It also frequently related to social inclusion and access to key services and facilities [57]. Most frequently, the concept of socially just or equitable development was discussed in relation to urban growth, considering the growing number of inhabitants in the cities and the speed of urbanization processes in various parts of the world. The concept of socially just urban development was introduced by Campbell in 1996 [58]. It meant development which shall address three major existing conflicts between economic growth, fair distribution of the results of this growth and protection of environment with presentation of nature resources. The author introduced a triangle, which should serve as a recommendation for policy planners to solve the first conflict between economic growth and equity, then the resource conflict and, further on, the development conflict. Participatory governance and engagement of various stakeholders on discussion of possible ways and solutions between these three conflicts was identified as an option for compromised oriented sustainable development.

The social justice principles were further applied to other policies domains. Jenkins et al. [59] suggested to apply these principles in regard to energy policy. According to Jenkins et al. [59], energy justice should evaluate areas where injustices occur, it should show which parts of society are ignored, it should analyze which processes exist for remediation and further on propose measures to reduce these injustices. The preliminary concern of the just and fair energy policy should be how to distribute benefits and burdens of various energy systems.

Until recently, energy policy was mainly concerned with energy systems and discussion about their effectiveness and efficiency. Now, the scientific discussion moves stronger to the direction of distributional, procedural and recognized based justice for energy production and consumption. While speaking about energy systems, all parts of the process are included such as mining, conversion, production, transportation, distribution, consumption and waste. Discussion about energy justice has potential to become a new framework which brings together research on energy production and consumption and on the ways how to achieve the goals of fair and just energy processes.

Speaking about energy transition, the term frequently used by politicians to describe decarbonization of energy generation, Heffron and McCauley [60] highlight the issue of the just transition, which addresses issues of energy justice, climate justice and environmental justice. Energy justice should also refer to the application of the concept of human rights across the entire energy lifecycle. Such just transition should also address principles of output and distribute justice while involving all stakeholders into decision-making processes and equally distributing burdens, risks and benefits of the energy transition process.

In relation to Arctic, the fair energy policy should address the question of the location of power plants and mining activities in the vicinity of indigenous people. It should also provide opportunities for indigenous people to engage into decision-making processes which affect their communities, their cultural values and way of life. Output justice of energy generation, transmission and distribution should be provided while burdens, risks and benefits of these activities are distributed equally among various groups and various level of governance. Procedural justice is not only about participation in decision-making processes, but it is also about mobilization of local knowledge. In this regard, various authors, also including Jenkins et al. [59], are calling for stronger protection of right of indigenous people such as Sami people who are spread across northern parts of Norway, Sweden, Finland and Russia and whose communities are heavily dependent on local ecosystems.

Understanding social sustainability is also closely linked to the issue of participatory management. With regard to the development of industrial commodities and infrastructure, participatory management is understood as a mechanism that facilitates the involvement of various stakeholders and social groups in the project in order to gather their feedback on the company's vision of the role in the region and the possibility of creating social infrastructure [61] and the details of project implementation, which also include transparency and accountability [62]. Data on European infrastructure projects show that joint management of infrastructure project planning has helped to implement projects with less social protests and negative consequences as well as more positive impact on local communities [56,63–66].

In this study, with regard to offshore oil and gas projects in the Arctic, we believe that the social aspect of sustainability should be reflected primarily through the creation of new competencies and new jobs. The social sustainability of a project means, among other things, new jobs and an increase in the requirements for staff competence, which in its turn will mean increasing the human potential of an oil and gas company.

2.2. Definition of "Strategic Sustainability"

Further, following the logic of this study, it is necessary to move to the concept of "strategic sustainability". In our opinion, strategic sustainability is the basis for the long-term development of a company or project. A project's strategic sustainability factor is important in an environment where offshore hydrocarbon production involves huge capital and operating costs, long payback periods and high uncertainty associated with price volatility and global environmental and geopolitical trends.

According to Sabanchiev [67] strategic sustainability refers to a certain ability of an industrial system (project, company), which is based not only on maintaining the integrity of the structure but also on achieving and developing strategic goals in a continuously changing (or variable) environment. In this interpretation, the strategic sustainability of a system (project/company) is achieved by establishing a balance between manageability (degree of control) and flexibility (mobility of the organization). In his scientific paper "Flexibility, manageability and strategic sustainability: concepts, relationships and evaluation" Sabanchiev presents an attempt to qualitatively assess the potential of flexibility and manageability of the organization, which will confirm the presence or absence of strategic sustainability.

In the scientific work of Galitskaya [68], strategic sustainability is aimed not only at the efficient use of production resources and the preservation of financial and economic stability over a long period of time under the conditions of a changing internal and external environment but also at increasing the cost of capital, which contributes to the sustainability of the industrial system, investment attractiveness and growth of income of its owners.

In his dissertation research, Dudin [69] strategic sustainability is viewed in terms of competitiveness and is expressed as a set of "manageable dynamic components" that ensure the continuous development of companies (organizations) in the right (right, right) balance. This is the ability to create, develop and maintain competitive advantages in a segmented commodity market for a long time, thus maintaining a proper level of liquidity, solvency and profitability of the industrial system in the conditions of changes in the external environment. The proposed definition of strategic sustainability considers competitiveness to be the "ability to produce or obtain and successfully implement innovations", which give rise to significant advantages that allow the company (organization) to move to a new modern level of development.

Kucheryavy in his scientific work [70] writes that the competitive advantages of the company's strategic sustainability include "the ability to adapt to current environmental requirements" (flexibility), development and growth of benefits and "compliance with the tactics of the moment" (innovation potential).

Baranenko and Shemetov [71] believe that strategic sustainability is the maintenance over a long period of time of the growing trend expressed by the system of key performance indicators of the industrial system. In this book, the authors consider strategic sustainability from three main aspects: financial sustainability, technological sustainability and organizational sustainability.

According to Terentyeva [72], ensuring strategic sustainability primarily means increasing market share and maintaining a leading position on the market and developing competitive advantages, including the development of innovative products.

The author Rychikhina [73] proves that the strategic stability of the industrial system is expressed through minimization of losses due to adverse environmental impacts, and under favorable circumstances—in the ability to effectively increase their assets, both tangible and intangible, which increases the survival of the enterprise in the event of adverse changes in the external environment in the future.

A critical analysis of the definitions is presented above showing that the authors are closer to the concept of sustainability. However, in the case of offshore oil and gas projects, these definitions are not suitable for strategic sustainability, since most of them do not reflect technological and socio-environmental aspects.

Alonzi in his scientific work "What is Project Sustainability?" [74] speaks about sustainability as the ability of the organization (company) to achieve its mission (strategy) in the long term. Looking at projects as temporary structures, Alonzi focuses on the fact that the result (or impact) of a project must be continued and developed after the project itself.

Many large Russian and foreign companies research strategic sustainability issues within the framework of corporate sustainability by publishing sustainability reports, based on which they define and highlight economic, environmental and social aspects of sustainability. According to Baumgartner and Ebner [75], strategic orientation and sustainability development of companies must be designed on the basis of an effective resolution of the existing problems (weaknesses) of the company (organization, projects), but in many cases, there is no link between the identified problems and the sustainability strategies of the company (organization, projects) in practice.

Baumgartner in the scientific work "Strategic perspectives of corporate sustainability management to develop a sustainable organization" [76] presents sustainable development as economic, environmental and social development that meets the needs of the present and does not prevent future generations from meeting their needs. This study reveals the relationship between strategic management and sustainable development, providing an open discussion for further empirical research.

Martens and Carvalho in their scientific work "Key factors of sustainability in project management context: A survey exploring the project managers' perspective" [77] identify four key factors that will contribute to the strategic sustainability of the company (organizations, projects): a sustainable innovative business model, stakeholder management, economic and competitive advantages, and environmental policy and resource saving.

Tharp in her scientific research "Project management and global sustainability" [78] speaks about the methods of sustainable development of the company (organization) as responsibility for the impact of its activities on customers, employees, shareholders, community and the environment in all aspects of its operations. This article focuses on the interdependence between companies and society as a whole, covering the following aspects: human rights, labor practices, the environment (sustainable use of resources, pollution prevention and climate change mitigation), fair operating practices (combating corruption, fair competition and respect for property rights), consumer issues (fair contract practices, dispute resolution and fair marketing), and community engagement.

Thus, the authors also define strategic sustainability as a set of financial, technological, market, environmental, social and other types of sustainability. These definitions: Alonzi [74], Baumgartner and Ebner [75], Baumgartner [76], Martens and Carvalho [77], Tharp [78]—are more appropriate for understanding the strategic sustainability of an offshore oil and gas project but do not reflect the specifics of the offshore fields, implementation environment or technology. It must be emphasized that here there are gaps in the theoretical basis for the definition of "strategic sustainability" of high-tech and archaically complex offshore oil and gas projects in the Arctic from a technical and managerial point of view.

2.3. Strategic Sustainability of the Offshore Oil and Gas Project

The offshore oil and gas project in the Arctic addresses a complex set of technological challenges. Its characteristics are related to geological, technological, macroeconomic, environmental and geopolitical factors. The financial efficiency of such a project is important, but it is equally important to develop the innovative component of the company, that is, unique technological solutions that can be used in the implementation of the project: the use of ice-resistant platforms or subsea production complexes, new exploration methods or transport and logistics technology systems will provide the company with a sustainable competitive advantage for several years ahead.

In addition, it is important to recognize that the long-term realization of the project is likely to be associated with market changes, falling or rising oil prices, reduced demand, increased impact of green energy in the face of CO_2 emissions reductions and the adoption of a number of international conventions (Paris Agreement and others) and substitution of traditional energy sources with alternatives. In particular, there are a number of other international agreements and target documents aimed at combating climate change. We put here citation from [79]: "Alongside its CO_2 commitments for 2030 and 2050, the EU should contribute to international efforts to limit emissions of short-lived climate pollutants such as black carbon and methane that further accelerate climactic changes in the Arctic. Coming from soot and up to 1500 times more powerful than CO_2, black carbon increases the melting rate of ice and snow. Methane is another greenhouse gas, 20 times more potent than CO_2, with vast reserves projected to be stored under the Arctic permafrost. The EU could limit emissions through the Convention on Long-Range Transboundary Air Pollution (UNECE CLRTAP); the amended Gothenburg Protocol, the Commission's Air Quality Package proposal; the Climate and

Clean Air Coalition; and engagement with Arctic Council initiatives such as the Task Force on Black Carbon and Methane".

All of these factors and limitations, which may also occur internationally, must be taken into account and taken into account by the company which must have alternative options for project implementation—to complete the project with commercial benefits. Environmental risks in the implementation of offshore oil and gas projects are very high—in this regard, the company must provide for the reliability of its technological systems, provide access to reliable oil spill response technologies and so on.

The authors believe that a systematic approach to assessing the sustainability of offshore Arctic oil and gas projects is appropriate. Summarizing the definitions of sustainability and strategic sustainability in the literature review presented above in the Sections 2.1–2.3 and complementing these definitions with the specifics of Arctic offshore oil and gas projects and their missions, including their social and environmental component, the authors propose four approaches to defining "strategic sustainability"—process, marginal, systemic, and competitive advantage-based (Figure 1).

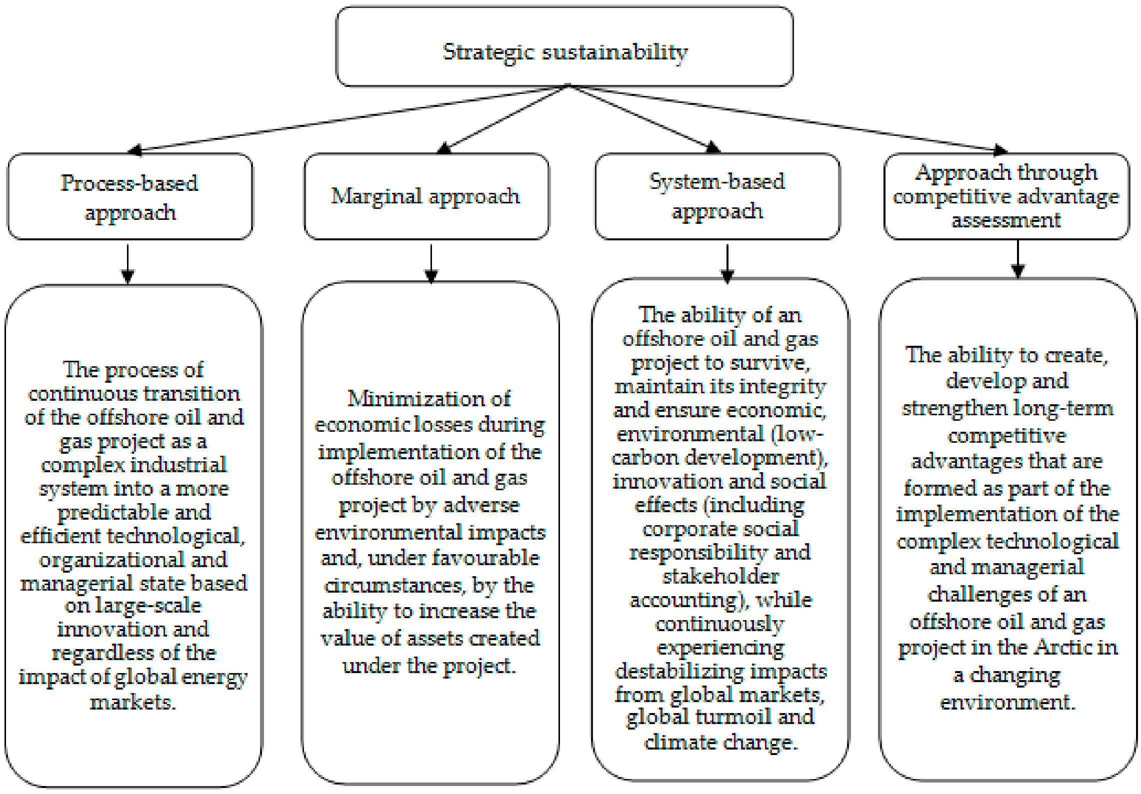

Figure 1. Classification of approaches to the definition of "strategic sustainability" of the offshore Arctic oil and gas project. Source: authors self-elaboration.

In general, the term "strategic sustainability" for an oil and gas Arctic offshore project should be understood as continuous improvement within the framework of the project, while achieving strategic goals and the ability to survive and preserve the long-term character of development under conditions of various risk events and phenomena, and above all under conditions of trends of CO_2 emission reduction and reduction in the use of fossil fuels in the global energy industry and thus unpredictable development of the situation on the world markets of energy carriers and products of their processing.

In this regard, the high risks of offshore Arctic oil and gas projects must be highlighted. Different aspects of risks are well reflected in the studies [80–91]. These studies describe in detail the subjective perception of risks, financial risks, management risks, project management risks and risks associated with social opposition.

2.4. Risks of Offshore Oil and Gas Projects

This study should address the specific risks of offshore oil and gas projects.

Voronina [92] and Fadeev et al. [93,94] believe that the development of hydrocarbon resources, particularly in the Arctic under extreme climatic conditions, the low sustainability of environmental systems and the complexity of engineering and transport infrastructure, is associated with the high capital intensity, complexity and heterogeneity of social processes, which makes offshore projects highly risky. Voronina in her paper [92] proposes the following division of the risk universe of Arctic shelf oil and gas development projects: geological risks, technical risks, transport risks, environmental risks, social risks, political risks, financial risks, including investment and commercial risks. The authors agree with this division. Let us characterize the main risks.

Geological risks arise during geological exploration and are due to insufficient study of the shelf, as well as high costs of drilling. These risks are manifested in the absence of oil and gas potential and non-confirmation of reserves.

Fadeev et al. [94], apart from technical risks, also highlight *technological risks*. Technological assessment of the availability of reserves for commercial development of a field is determined on the basis of the possibility of using existing technical facilities as well as prospective technical developments that can be used for fields at later stages of development. It should be noted that the factor of technological availability of fields in the Arctic region is the first basic criterion for their differentiation by industrial importance.

At present, real field development technologies exist only for the transit zone and the part of the shelf where there is no continuous ice.

Technologically inaccessible reserves and resources are allocated in those areas where, due to geological or climatic conditions, there are no actually working technologies for the industrial development of identified oil and gas fields. In particular, this factor is critical in those areas of the Arctic shelf where ice is distributed at significant sea depths [94].

Technological and transport risks of the development stage, typical for the shelf of the Northern seas, are associated with the complexity (and sometimes lack) of technologies, increased probability of equipment failure (especially in Arctic conditions), lack of experience in the transportation of hydrocarbons in significant volumes, shortage of tankers and icebreakers, etc. [94]. The choice of technology and technical means for the transportation of resources is determined by the influence of a number of factors: the geographical position of the water area, the depth of the sea, the volume of transported products, the distance of transportation, etc.

Perspectives on the development of offshore fields in Russia are also associated with areas that are characterized by heavy and very heavy ice conditions and relatively small depths of the sea. These include the Pechora sea, the Sakhalin shelf, the Kara sea and the East Arctic waters [94]. There are very significant differences between these areas in terms of transport infrastructure. The Sakhalin shelf with small distances of transportation of production to the coast is especially allocated. In addition, the infrastructure for oil and gas production is already developed on the Sakhalin coast, adjacent to the sea fields. In such conditions, for the Sakhalin shelf fields, it seems appropriate to focus on the laying of pipelines from each field to the shore, followed by their connection to the coastal communications. Therefore, there appears a whole complex of technical and technological tasks applicable to shallow-water gas pipelines. The only fundamental difference is the absence of permafrost on Sakhalin.

In the rest of the Arctic, the situation is fundamentally different: here either there are no communications with the coastal zone, or they are underdeveloped. To solve the problem of transporting oil in these conditions, it is necessary to construct loading terminals for tankers. At the same time, in order to ensure year-round oil transportation, for example, from the fields of the East Arctic seas, where the ice-free period is limited to 1.5–2.0 months, non-traditional means of transport such as icebreaker tankers will be required [94].

The development stage is also characterized by *environmental risks* associated with the possibility of causing serious damage to the environment and the subsequent costs of its liquidation and compensation.

This risk factor can occur at any stage of the operations, from offshore hydrocarbon production to the transportation of oil or gas products. As a result, the preservation of the Arctic's natural environment and its ecological balance can be disrupted, and people's livelihoods can be endangered. Global statistics show that offshore development and the transportation of oil and gas by water are among the most environmentally hazardous activities.

The nature of risks, their probability and potential damage at various stages of prospecting, exploration and development are analyzed. It should be borne in mind that oil spill incidents can have catastrophic consequences for the living resources of the Arctic seas. The potential damage may amount to tens of billions of dollars. In any case, the number of fines in the Russian Arctic shelf will be significantly higher than in the case of an oil spill by a tanker in the Pradho Bay field in Alaska or a fire on a platform operating in the Gulf of Mexico [94].

Accidents on offshore drilling platforms can be accompanied not only by extremely serious environmental consequences but also by large human victims due to the thermal effects of fire and the toxicity of combustion products, due to the limited platform area and evacuation difficulties.

Along with this, an analysis of accidents on oil and gas platforms shows a decrease in the number of accidents with catastrophic consequences in recent years (the death of a huge number of people, large-scale environmental pollution, major material damage), which may be associated with technological and design improvements of platforms and the use of modern security systems [94].

Legal regulations and liability insurance might help to reduce the risks, but sometimes the slightest mistake can lead to significant adverse consequences.

When approaching the moment of completion of the field, there are *risks associated with the deterioration of equipment and infrastructure* [94]. On the one hand, this leads to an increase in the environmental risks of the investor, as the probability of equipment failure and serious damage to the environment increases. On the other hand, after the completion of the project, the state remains with objects that are either not suitable for further use or require significant funds to maintain them in working condition.

There are *liquidation risks*, manifested in the possible absence of the subsoil users and the state of funds for the implementation of liquidation work [94]. In particular, the United Kingdom and Norway, which have long been producing oil and gas on the shelf, have already encountered such a problem. To reduce this risk, liquidation funds are created, and a deduction from the tax base of the costs of creating liquidation funds is made. According to Russian legislation, the formation of a liquidation fund—the most reliable mechanism for reducing liquidation risks—is possible only when using the production sharing mode.

Social risks are related to the possible negative consequences from the projects on the quality of life and the original culture of the people living in the Arctic region as well as the uneven distribution of benefits and risks of the projects between extracting companies and local communities. Such projects might also lead to the increased inequality within social groups and between various regions as well as to social instability. There is a need to strike a balance between the interests of extractive companies and the population of the Arctic territories, taking into account their ethnic characteristics, lifestyle which is closely connected to the nature and existing possibilities to participate in decision-making processes which affect their communities as well as the existence of social impact assessment regulation.

Risks of increased use of non-fossil fuel in connection with the fight against climate change. Global oil and gas companies forecast an increase in the share of renewable energy sources (RES) [95,96], and the Paris Convention and other documents dictate the need to develop zero emission and hydrocarbon development technologies.

In particular, BP (formerly British Petroleum) stated that the time for the growing global demand for oil has passed. The need for fossil fuels has already peaked and will face an unprecedented decline over the next few decades. The Guardian [97] reports this with reference to BP's annual report.

In September 2020 BP published a report on its energy prospects [96]. According to the report, oil is likely to be replaced by clean electricity from wind farms, photovoltaic panels and other renewable energy sources.

According to the report [96], demand for oil will decline by 55% over the next 30 years. If as many countries as possible comply with the Paris Climate Agreement, demand for oil will fall by 80% by 2050.

The growing popularity of electric cars may also have an impact on the demand for oil. Another factor that is reducing the demand for oil in the coming years is the new measures to restrict plastic, which requires petrochemical products made from fossil fuels.

In August 2020 BP presented plans to increase its investment into low-carbon technologies eightfold by 2025 and tenfold by 2030, reducing fossil fuel production by 40% compared to 2019 [92]. In September 2020, the company took its first step in the offshore wind energy business by investing $1.1 billion [97].

This means that other oil and gas companies will also diversify into low-carbon development projects. There may be a decline in demand for fossil fuels, and this will make expensive offshore projects impossible—the era of high oil prices will be gone forever.

The development phase is also characterized by high *economic risks* associated with high capital intensity and duration of offshore development projects. Thus, even a slight increase in costs can lead to a significant increase in the payback period and reduce the return on invested capital [94]. This circumstance places special emphasis on the management of the development of offshore oil and gas fields.

In addition, the indicators arising from the volume of reserves and geological resources are deterministic and therefore do not sufficiently consider the investment risks associated with their non-confirmation, especially in the initial stages of exploration. This should be taken into account when planning exploration and field development on the Arctic platform, where the cost of drilling each well can be in the hundreds of millions of dollars [94].

There are also *risks of emergency situations* in the Arctic, which are discussed in scientific works [98]:

- Natural character: dangerous hydrometeorological phenomena, morphology and dynamics of the Arctic seashore, the impact of ice formations, gas hydrates, geological and natural processes hazardous to oil and gas industry structures on the Western Arctic shelf of Russia, permafrost degradation;
- Risks of oil spills, risks of permafrost facilities, risks of gas transportation on the sea floor, risks of accidents at hydroelectric power plants built in the permafrost zone, risks of accidents at potentially hazardous industrial enterprises, risks of shipwrecks in the Arctic seas, risks of aviation accidents in the Arctic;
- Ecological character: anthropogenic disturbance of the natural landscapes of the Arctic zone, environmental risks of oil spills on the Arctic platform, the impact of climate change on the Arctic environment [99];
- Risks associated with the use of the Northern Sea Route [98,100].

Analysis of these risks shows that the implementation of projects to develop oil and gas resources of the Arctic platform requires the resolution of various problems: the implementation of projects in the Arctic conditions requires the introduction of non-trivial measures of innovative nature, which in turn increases the risks. Therefore, it is necessary to be able to analyze, assess and manage risks rather than avoid them.

Fixing the values of changes in project development over a long period of time allows us to identify a trend. Any trend can be expressed through trends that are rising and falling. In order to achieve strategic sustainability, the project, its timing and economic performance must strive to establish and maintain an upward trend [94]. Strategic sustainability has several aspects: achievement of a certain level of indicators within a given timeframe (these can be both natural and cost indicators—in particular profitability), project repeatability or replicability, and risk tolerance.

With regard to the criteria for assessing the strategic sustainability of an offshore oil and gas project, the authors note the need to assess the project from the point of view of the geological verifiability of reserves, technological equipment, financial efficiency and social and environmental factors.

3. Materials and Methods

The research materials are monographs and scientific articles, applied works of Russian and foreign scientists devoted to the theory and practice of strategic management in the oil and gas complex. In the course of the research, periodicals and materials from scientific and practical conferences were also used. The method of hierarchy analysis was used in the study.

3.1. Criteria for Assessing Strategic Sustainability

Based on the studies conducted in Section 2, the authors consider it appropriate to identify the following key strategic sustainability objectives affecting the sustainable development of Arctic marine projects—investment, technological, geological, social and environmental (Table 1).

Table 1. Strategic sustainability goals for marine projects in the Arctic.

Objectives	Description
Investment	It is necessary to understand the profitability of the projects and the limits of the project cost per unit. It is also very important to understand and predict the level of exploration costs due to the low degree of exploration of offshore fields in the Arctic.
Technological	Implementation of projects in the Pechora, Kara and Eastern Arctic Seas will require the development of new technical solutions and the adaptation of existing ones. Technological sanctions from the USA and EU countries make project implementation difficult.
Geological	The success and sustainability of reserves growth are the most important targets for the offshore oil and gas project in the Arctic.
Social criteria and stakeholders	The Company has the set of knowledge and experience required for the customer to implement current stages of projects. The full range of offshore competencies currently lacking in many Russian oil and gas companies and in the country as a whole may be in demand for the implementation of offshore Arctic projects.
Ecology	Ensure environmental safety and biodiversity conservation at exploration and mining sites. Zero CO_2 emissions projects are also an important objective.

Source: authors self-elaboration.

The authors propose to develop a methodology for assessing the strategic sustainability of offshore projects, taking into account the objectives set out in Table 1 and identifying specific criteria for these projects based on them. The strategic sustainability will be assessed on the basis of an integral sustainability indicator.

The grinding projects considered by the authors form a significant resource potential (geological resources of about 15 billion tons of oil equivalent) [94]; however, they are at the "Search" stage and are characterized by varying degrees of complexity and geological and geophysical exploration, which determines a significant range of assessment of their technical and economic performance.

The study examined 5 projects located in the Pechora, Kara and Eastern Arctic Seas, all of which are in the exploration phase.

The specific criteria for offshore oil and gas projects for which a new methodology is being developed are divided into two levels—sustainability groups and indicators that characterize them (the grouping result is presented in Table 2). The first-tier criteria include five groups: investment, technology, geological and field, social and environmental. The second-tier criteria include the indicators presented in Table 2.

Table 2. Grouping of assessment criteria for offshore oil and gas projects.

Investment Criteria
Commissioning time
UTC (Unit Total Cost)
EMV (Expected Monetary Value)
Expenditure on the geological exploration program
Technological criteria
Technological possibility of project implementation
EU and US sanctions
Oil and gas field complexity category
Geological and operational criteria
Potential for accumulated production
Success evaluation
P = (Extractable resources of the entity—minimum required resource size)/Extractable resources of the entity × gCOS [1] × 100
Difference in accumulated production P10 [2]/P50
Geological exploration
Social and HR criteria
New jobs
Inflow of highly qualified staff into the project from other companies
Growth of competencies of company employees implementing the project
Mechanisms for feedback from public organizations and regional management structures.
Ecological criteria
Reliable oil spill response technology
Preservation of marine ecosystems and biodiversity
Minimization of CO_2 emissions during extraction and transportation
Creation of additional insurance funds of a financial nature to ensure the elimination (minimization) of possible environmental damage.

Source: authors self-elaboration. Note: [1] gCOS (Chance of Success)—geological probability of project success; [2] P10—the maximum estimated resource amount supported by a probability of 0.1.

Thus, we reviewed the concept of "sustainability", the concept of "strategic sustainability", the problems of strategic sustainability of an offshore oil and gas project and the risks of offshore oil and gas projects. We then proposed criteria for assessing strategic sustainability. Further on, we provide description of the most appropriate methods, from our point of view, for an assessment of the strategic sustainability of offshore oil and gas projects.

3.2. Methods for Assessing Strategic Sustainability

Arctic oil and gas projects are characterized by unique technological projects. Many potential projects have no analogues. In this regard, the most appropriate methods for assessing the strategic sustainability of offshore oil and gas projects are those of assessing and comparing multi-criteria alternatives.

Currently, the most widely used and well researched methods for assessing and comparing multi-criteria alternatives are [101]:

- Methods based on quantitative measurements—multi-criteria utility theory (MAUT—Multi-Attribute Utility Theory). The founders of the method are Ralph L. Keeney and Howard Raiffa [102,103]. The advantages of the methods lie in the possibility of mathematical justification of a certain type of general utility function based on the individual preferences of the decision maker, as well as in the possibility of evaluating alternatives that can be formed after the assessment has been carried out. The disadvantages of the methods are that they are time and effort consuming for the decision maker (regardless of the number of alternatives being evaluated) and the need for accurate quantitative measurements of the weighting characteristics of the decision maker's evaluation criteria;

- Lotfi Zadeh suggested methods based on the theory of fuzzy sets in his works [104,105]. The theory of fuzzy sets, although usually used in practical applications on its own, is in a sense reduced to random set theory and thus to probability theory;
- Methods based on quantitative measurements but using several indicators when comparing alternatives—group of methods ELECTRE (Elimination Et Choix Traduisantla Realite); developed in his works Bernard Roy [106,107]. The plus of the methods was that there was no need for a one-stage definition of the decision maker's preferences and that it was possible to form opinions gradually and reasonably well-founded. However, the disadvantage of the methods was the complexity of the process of determining coefficients of significance and the possibility of erroneous opinions in the selection of nuclei with minimal dominance of one structurally complex alternative over another;
- Methods based on qualitative measurements, without moving to quantitative variables (Verbal Decision Analysis (VDA)) [108,109]. Most decision makers recognize the deep contradictions between the requirements of regulatory methods and the capacity of the human information processing system. An attempt to overcome these contradictions is the verbal decision analysis approach based on psychological criteria, i.e., these methods take into account cognitive and behavioral aspects. However, the task of singling out the best of multi-criteria alternatives is quite complex for a person: thus, when singling out a subset of the best alternatives, subjects can remove the dominant alternatives and leave the dominant ones behind. In addition, there may be a situation where cycles appear on the multitude of alternatives being compared;
- Simple multi-criteria assessment method SMART, first formalized and developed in the works [110,111], is notable for its simplicity and reliability in practical application. In addition, the sensitivity check for weight changes makes it possible to take into account the impact of inaccuracies in measurements and the possible relationship between criteria. However, this method does not take into account the possible dependence of measurements and is not additive in determining the overall value of the alternative;
- Methods based on qualitative measurements, the results of which are converted into quantitative form—methods of analytical hierarchy (AHP—Analytic Hierarchy Process). This method was developed by the American mathematician Saati, Thomas L. [112,113]. The method of hierarchical analysis is used worldwide to make decisions in situations ranging from interstate management to commercial and private problems in business, industry, healthcare and education. Along with mathematics, it is also based on psychological aspects.

AHP does not define the "right" solution for the decision maker (DM) but allows the decision maker to interactively find an alternative that best meets their understanding of the problem and the requirements for solving it.

With the help of the AHP, it is possible to structure the complex problem of decision-making in a hierarchical manner clearly and rationally, and to compare and quantify alternative solutions.

The analysis of the decision-making problem in the AHP begins with the construction of a hierarchical structure that includes the objective, criteria, alternatives and other factors affecting the election. This structure reflects the decision maker's understanding of the problem.

Each element of the hierarchy may represent different aspects of a problem, taking into account both material and non-material parameters, measurable quantitative and qualitative characteristics, objective data and subjective expert assessments. In other words, the AHP's analysis of the decision-making situation is no different from the argumentation processes and methods used at an intuitive level.

The next step in the analysis is to identify priorities that reflect the relative importance or desirability of elements of the hierarchical structure that has been built using a paired comparison procedure. Unbalanced priorities allow for the reasonable exposure of heterogeneous factors to comparison, which distinguishes AHP significantly.

The Saati method is based on a paired comparison of alternatives for each criterion and a comparison of criteria in pairs, taking into account the importance of the objective. All comparisons in this method are therefore made in pairs, i.e., in the simplest and most obvious way.

For comparison, Saati suggested applying qualitative features, which are then converted into quantitative features on a 9-point scale (although it is possible that an object may be more than 9 times larger than another criterion, this scale is usually sufficient to reflect a qualitative ratio). If the DM cannot choose between two qualitative characteristics, if there is an intermediate opinion, Saati recommends using intermediate points 2, 4, 6, 8. These comparison possibilities can be defined in various ways: by subjective opinion, expert evaluation, voting, etc.

At the final stage of the analysis, a synthesis of hierarchical priorities is carried out, with the priorities of alternative solutions calculated in relation to the main objective. The best alternative is the one that has the highest priority value.

Despite the need to solve the task from scratch in the event of the emergence of any new alternative that was not originally envisaged and the peculiarity of the method of transition from qualitative to quantitative measurements, this method has undeniable advantages: the obvious focus of the decision maker's efforts on comparing the existing alternatives, which, with a small number of them, objectively reduces the labor intensity of the entire process; also, this method is not required to absolutize certain estimates. With the help of the AHP, it is possible to structure the complex problem of decision-making in a hierarchical manner clearly and rationally and to compare and quantify alternative solutions.

In this regard, we consider the hierarchy analysis method (AHP) to be the most appropriate one for assessing the strategic sustainability of offshore oil and gas projects—a mathematical tool for a systematic approach to complex problems in decision-making.

The algorithm proposed by the authors is to compare the evaluation criteria using the scale of relations by Saati, further building a normalized matrix, finding a priority vector and then evaluating the level of matrix inconsistency. This is done for each level of evaluation criteria for offshore oil and gas projects.

Let us consider this algorithm using the Company's Arctic oil and gas projects as an example. Therefore, the assessment of the strategic sustainability of the Company's Arctic oil and gas projects begins with a pairwise comparison of existing assessment criteria. To compare the relative importance of the criteria, we will use the scale of relations by Saati [113] (Table 3).

Table 3. Scale of evaluation of hierarchies by Saati.

Meaning		Interpretation
1	–	equivalence
3	–	moderate superiority
5	–	strong superiority
7	–	very strong superiority
9	–	highest (extreme) superiority
2, 4, 6, 8	–	appropriate intermediate values

Further on, we are moving to the description of the results from our survey.

4. Results

The authors involved experts from four companies: Gazprom Neft PJSC (Saint Petersburg, Russia), Gazprom Neft-Sakhalin LLC (Saint Petersburg, Russia), Rosneft PJSC (Saint Petersburg, Russia) and

Gazprom Neft Shelf LLC (Saint Petersburg, Russia). The survey was impersonal, 14 experts were selected, and the level of positions ranged from chief specialist to head of department. The experts assigned points, each in their own table (Tables 4 and A2–A6 (see Appendix A)).

Table 4. Evaluation of Level 1 criteria.

Criteria	Investment Sustainability	Technological Stability	Geological Stability	Social Sustainability	Environmental Sustainability
Investment sustainability	1/1	1/2	1/3	3/1	3/1
Technological stability	2/1	1/1	1/3	3/1	3/1
Sustainability in terms of geology	3/1	3/1	1/1	4/1	3/1
Social sustainability	1/3	1/3	1/4	1/1	1/3
Environmental sustainability	1/3	1/3	1/3	3/1	1/1
Amount	6.67	5.17	2.25	14.00	10.33

Source: results of the experts' evaluation.

Let us look at the first level criteria. The results of the expert evaluation are presented in Table 4. The table presents the average results of the peer review.

Experts' evaluations will be explained. For example, in Table 4, investment sustainability in relation to technological sustainability has a score of 1/2 (accordingly, technological stability in relation to investment stability is estimated at 2/1)—this means that experts believe that the importance of technological sustainability indicators "moderately exceeds" the importance of investment sustainability indicators. Moreover, the geological sustainability assessment for environmental sustainability has a 3/1 rating (respectively, environmental sustainability in relation to geological sustainability is estimated at 1/3)—this means that geological sustainability has a "strong advantage" over environmental sustainability, etc.

The next step is to build a normalized matrix. For this purpose, we divide the sum of each column into each column element. The results of the calculations are in Table A1 (see Appendix A).

We will find a priority vector for the first level criteria. For this purpose, each sum of rows in the previous table will be divided by the number of elements. The results of the calculations are presented in Table 5.

Table 5. Calculation of the first level criteria priority vector.

Level 1 Criteria	Meaning
Investment sustainability	0.18
Technological stability	0.23
Sustainability in terms of geology	0.42
Social sustainability	0.06
Environmental sustainability	0.11

Source: calculations by the authors.

As the columns of the normalized matrix are not identical, the original comparison matrix must be checked for consistency. To do this, we multiply the comparison matrix by a priority vector. Then we find the consistency index. If the index does not exceed 0.1, then the matrix is found correctly. Calculations have shown that the level of inconsistency is acceptable ($0.09 < 0.1$).

The next step was to build a matrix of paired comparisons of the second level elements against each of the first level criteria. For each matrix, a priority vector, consistency factor, stochastic consistency factor and consistency factor were calculated. The average results of the expert evaluation are presented in Tables A2–A6 (see Appendix A).

The next step is to build a normalized matrix. To do this, we divide the sum of each column into each column element. The results of the calculations are in Tables A7–A11 (see Appendix A).

We will find a priority vector for the second level criteria (see Table 6). To do this, divide each sum of rows in Table A9 of Appendix A by the number of elements.

Table 6. Calculation of the second level criteria priority vector.

Level 2 Criteria	Meaning
Commissioning time	0.09
UTC (Unit Total Cost)	0.23
EMV (Expected Monetary Value)	0.47
Expenditure on the geological exploration program	0.19
Technological possibility of project implementation	0.12
Sanctions	0.67
Oil and gas field complexity category	0.29
Potential for accumulated production	0.17
Success evaluation	0.18
Difference in accumulated production P10/P50	0.20
Geological exploration	0.45
New jobs	0.13
Inflow of highly qualified staff into the project from other companies	0.25
Growth of competencies of company employees implementing the project	0.38
Mechanisms for feedback from public organizations and regional management structures	0.24
Reliable oil spill response technology	0.20
Preservation of marine ecosystems and biodiversity	0.46
Minimization of CO_2 emissions during extraction and transportation	0.14
Creation of additional insurance funds of a financial nature	0.19

Source: calculations by the authors.

As the columns of the normalized matrix are not identical, we also checked the original comparison matrix for consistency. Our calculations have shown that the level of inconsistency of this matrix is also acceptable (0.07 < 0.1).

Total investment sustainability index (ISI):

$$ISI = w_1 \times \text{Termission period} + w_2 \times \text{UTC} + w_3 \times \text{EMV} + w_4 \times \text{Program costs}, \tag{1}$$

where w_i is the weight of the respective factors selected for the investment sustainability study.

Generalized technological stability indicator (TSI):

$$TSI = w_1 \times \text{Technological feasibility of project implementation} + w_2 \times \text{Sanctions} + w_3 \times \text{Category of complexity}, \tag{2}$$

where w_i is the weight of the respective factors selected for the technological stability study.

Generalized geological stability indicator (GSI):

$$GSI = w_1 \times \text{Success Potential of Accumulated Production} + w_2 \times \text{Success Assessment} + w_3 \times \text{Accumulated Production Difference P10/P50} + w_4 \times \text{Geological Survey}, \tag{3}$$

where w_i is the weight of the respective factors selected for the geological stability study.

Total Social Stability Index (SSI):

$$SSI = w_1 \times \text{New jobs} + w_2 \times \text{Inflow of highly qualified personnel into the project from other companies} + w_3 \times \text{Competence gap of employees implementing the project} + w_4 \times \text{Mechanisms for feedback from public organizations and regional structures}, \tag{4}$$

where w_i is the weight of the relevant factors selected for the social sustainability study.

Generalized Environmental Sustainability Index (ESI):

$$\text{ESI} = w_1 \times \text{Sustainability of oil spill response technologies} + w_2 \times \text{Saving marine ecosystems and biodiversity} + w_3 \times \text{Minimizing } CO_2 \text{ emissions during extraction and transportation} + w_4 \times \text{Creating additional financial insurance funds,} \quad (5)$$

where w_i is the weight of the respective factors selected for the environmental sustainability study.

The strategic sustainability of the projects (SSP) will be based on a formula:

$$\text{SSP} = 0.18 \times \text{ISI} + 0.23 \times \text{TSI} + 0.42 \times \text{GSI} + 0.06 \times \text{SSI} + 0.11 \times \text{ESI}, \quad (6)$$

where ISI is investment sustainability; TSI is technological sustainability; GSI is geological sustainability; SSI is social sustainability; ESI is environmental sustainability; and 0.18, 0.23, 0.42, 0.06 and 0.11 are weights of the first level criteria presented by the experts (see Table 5). The calculation of the strategic sustainability of the projects is presented in Table 7.

Table 7. Calculation of the strategic sustainability of the Company's offshore projects.

Project	ISI	TSI	GSI	SSI	ESI	Strategic Sustainability of the Project (SSP)
Project 1	0.8	1.3	1.7	1.32	1.20	1.37
Project 2	1.7	2.9	1.0	2.15	0.95	1.64
Project 3	0.6	2.5	0.8	1.62	1.51	1.29
Project 4	1.2	1.5	1.5	1.28	0.35	1.31
Project 5	0.4	0.7	1.3	0.99	1.02	0.95

Source: calculations by the authors.

To make it clear which offshore projects are more strategically sustainable and which are less so, we suggest building a matrix consisting of two quadrants (see Figure 2). On the vertical axis, we will postpone the strategic stability values obtained for offshore projects, with a maximum of 1.7 and a minimum of 0.8 for the vertical axis. The horizontal axis corresponds to the middle of this interval—the value of 1.25. Projects falling in the upper quadrant (for our calculations SSP ≥ 1.25) are strategically stable, and projects falling in the lower quadrant (SSP < 1.25) are less strategically stable.

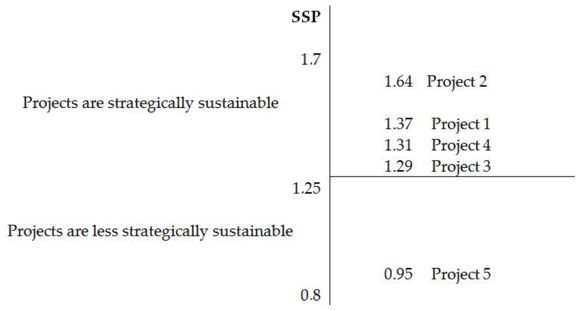

Figure 2. Interpretation of the calculation of the strategic stability of the Company's offshore projects. Source: authors self-elaboration.

Hence, Project 2 (SSP = 1.64), Project 1 (SSP = 1.37), Project 4 (SSP = 1.31) and Project 3 (SSP = 1.29) are the most strategically sustainable.

Project 5 (SSP = 0.95) is less strategically sustainable; they are long-term investment projects that require the development of new technological solutions during the transition to operations but have a significant level of reserves.

Of course, the achieved results should be discussed, and the authors are ready to offer critical comments and opportunities for improving approaches to strategic sustainability assessment and will consider these aspects further.

5. Discussion

The proposed methodology is mathematically sound and takes into account the specifics of offshore oil and gas project evaluation.

The proposed strategic sustainability assessment algorithm includes an assessment of various aspects of implementing offshore oil and gas projects. When gathering long-term information on the strategic sustainability indicator, it is possible to draw conclusions about the project's development trends and provide recommendations on its development. However, we do not believe that the system of criteria is conclusive. Such a system must be developed taking into account the changes taking place in the global energy industry.

The authors proposed specific criteria for assessing the strategic sustainability of offshore oil and gas projects, divided into five groups: investment, technological, geological-field, social and environmental. The results obtained by the authors showed that the highest weight, according to experts, is given to geological stability—0.42. The second most important group is technological sustainability—0.23, followed by investment sustainability—0.18, environmental sustainability—0.11, and social sustainability—0.06. Currently, technical and geological factors of the project implementation are the most important among Russian managers and specialists, which in terms of long-term development and the possible impact of damage to the environmental stability of the Arctic raises some concerns. In our view, companies must strengthen their "sustainable development policy" and implement a set of measures to facilitate the development of offshore oil and gas projects in the Arctic under conditions of ecological balance and social orientation. Understanding the dynamics of global energy development and the importance of low-carbon technologies, it is advisable to supplement the strategic sustainability assessment with criteria related to the minimization of greenhouse gas emissions at all stages of the technological cycle, for example, assessing the possibility of using sequestration technologies in case of high CO_2 content (in produced natural gas) or assessing the reduction of methane losses during transportation. The development of competencies, the role of innovative managers, the growth of social responsibility and the strengthening of relationships with public organizations are also key areas that must be taken into account when developing criteria for assessing the strategic sustainability of offshore oil and gas projects.

As a discussion, the authors also offer recommendations for the development of a strategic management system that will expand relevant assessment criteria and improve the quality of strategic sustainability assessment of marine projects in the Arctic (Table 8).

An important aspect that the authors would like to point out, and which is important for future generations and sustainability, is this: you cannot produce marine hydrocarbons unless you have a set of reliable measures in place that can preserve the Arctic's ecology. Marine projects must be ranked according to the degree to which environmental risks are minimized, and a set of criteria must be developed to ensure the safety of marine mining operations.

Particular attention needs to be paid to the Arctic shelf oil spills (see paragraph 5 of the Table 8 for this criterion) that could have serious environmental consequences. In the Arctic, it is important to highlight features that complicate the response to oil spills, such as the polar night, waves, currents, poor infrastructure and the lack of modern response equipment for Russian companies. Oil spill response methods need to be developed, but the authors suggest that the most important way to ensure the sustainability of offshore projects should be to reduce the probability of spills and minimize accidents in Arctic offshore fields.

Criteria related to ensuring environmental safety must be introduced into the system of strategic sustainability indicators.

For example, projects in which ecological risks can be managed are a priority for implementation. These are projects that involve the presence of technical means to reduce environmental risks and practical experience. Offshore projects, for example, may include those where drilling can be done from shore.

In the light of the proposed recommendations, it is possible to further develop a system of indicators to be taken into account in assessing the strategic sustainability of offshore oil and gas projects.

Table 8. Development of offshore projects to further define criteria for strategic sustainability assessment.

Areas of Development	Recommendations
1. Finance	– Formation of mechanisms for attracting financing from partners and delegation of geological risks at the exploration stage. – Changing the methodology for investment assessment and decision-making for projects with a long investment phase.
2. Technology	– Implementation of the import substitution strategy—an increase in the share of domestic equipment. – Use of technology partners and cluster mechanisms. – Development of interaction with suppliers. – Development of digital technologies.
3. Logistics and infrastructure	– Ensuring safe use of technical means and industrial safety development. – Ice situation management. – Development of the companies' own specialized fleet. – Development of a strategy to protect against dangerous ice phenomena and negative temperatures. – Development and restoration of logistics infrastructure.
4. People and processes	– Developing technical competencies in offshore drilling, seismic, engineering, logistics and HSE (health, safety and environment). – Management team development. – Development of project competencies, project management methodology and formation of project teams. – Formation of methodology and development of competencies in partnership management.
5. HSE (health, safety and environment)	– Improvement of industrial safety culture. – Development of measures to prevent oil spills and ensure readiness of forces and facilities. – Development of a strategy for emergency rescue, oil spill response and emergency medical evacuation. – Development of approaches to environmental protection of work and waste disposal. – Development of a system of criteria for the least and most dangerous projects from an environmental point of view.
6. External interactions and keeping track of global trends	– Attracting partners to implement offshore projects. – Interaction with the state (legal and regulatory support, elimination of administrative barriers). – Development of new standards and harmonization of existing standards to support offshore exploration, production and transportation. – Search for development directions, taking into account the synergy effect of developing active regions of marine and onshore production. – Accounting for low-carbon energy development. – Diversification of the oil and gas business.

Source: authors self-elaboration.

The authors assume that the results of the author's study to assess the strategic sustainability of offshore hydrocarbon field development projects are applicable for making strategic decisions regarding the prospects for developing Arctic shelf fields.

6. Conclusions

The authors have conducted studies of theoretical approaches to determining “the sustainability” of industrial systems and projects. The aspect that unites the approaches of different scientists to the definition of “strategic sustainability” is the long-term nature of environmental, social, economic and technological sustainability.

The authors propose a systematic approach, which defines strategic sustainability as the ability of an offshore oil and gas project to survive, preserve its integrity and ensure economic, environmental (low-carbon development), innovative and social effects (including corporate social responsibility and consideration of stakeholders’ interests) with the constant destabilizing impact of global markets, global turmoil and the fight against climate change.

The key risks of offshore projects, such as technological, geological, financial, social, environmental, transport and other risks, have been identified, which together with the approach to the concept of “strategic sustainability” have allowed the development of a system of criteria for assessing the strategic sustainability of an offshore oil and gas project. The authors also highlighted the risks of increased use of non-fossil fuels due to climate change, which are not reflected in the system of indicators but may be a serious challenge that significantly limits the implementation of offshore oil and gas projects in the future.

Specific criteria for assessing the strategic sustainability of an offshore oil and gas project have been defined, including five groups of first level criteria: investment, technological, geological, social and environmental, with four (three technological) specific indicators—second level criteria. On the basis of these criteria, a comprehensive indicator assessing the project’s strategic sustainability has been formed.

The methods for solving multi-criteria tasks were analyzed and the hierarchy analysis method was chosen as the most suitable method for the conditions of developing unique offshore oil and gas projects.

The strategic sustainability of existing offshore projects in the Russian Arctic shelf was assessed with the involvement of experts from the following companies: Gazprom Neft PJSC, Gazprom Neft-Sakhalin LLC, Rosneft PJSC and Gazprom Neft Shelf LLC. Experts from these companies evaluated and ranked specific criteria for assessing the strategic sustainability of five offshore oil and gas projects. This assessment was conducted with application of a questionnaire developed by the authors. On the basis of these assessments, the authors made calculations based on methodology which they developed. The authors assessed the sustainability of the projects based on a comprehensive indicator also developed by the authors that takes into account investment, technological, geological, social and environmental sustainability.

The authors believe that the developed approach to strategic sustainability assessment will be useful for Arctic oil and gas projects, and with further improvements, it will provide practical guidance for managers of oil and gas companies.

Recommendations have been provided to develop a system of indicators for assessing the strategic sustainability of offshore oil and gas projects within the following areas of strategic management: finance, technology, logistics and infrastructure, people and processes, HSE, external interactions and global trends.

The authors believe that the development of the Arctic offshore fields should be carried out “step by step”, with particular care for the environment and with the understanding that the possible development of (especially large-scale) offshore Arctic hydrocarbon resources is fundamentally inconsistent with the concept of sustainable development. It is often better to develop onshore projects in old oil and gas fields and to increase oil recovery than to start developing new projects in the Arctic. As a result, environmental standards need to be reviewed and tightened. It is very important to determine the level of risk of a given project, the more complex the natural and climatic conditions are and the poorer the infrastructure is, the higher the environmental risks and the more difficult it is to talk about sustainability. After all, the authors admit that if there is no certainty about the environmental safety of offshore carbon projects in the Arctic, then such projects should not be implemented.

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Appendix A

Table A1. Results of normalized assessment of the relative importance of Level 1 criteria.

Criteria	Investment Sustainability	Technological Stability	Geological Stability	Social Sustainability	Environmental Sustainability	Amount
Investment sustainability	0.15	0.10	0.15	0.22	0.29	0.90
Technological stability	0.30	0.19	0.15	0.21	0.29	1.15
Sustainability in terms of geology	0.45	0.58	0.44	0.29	0.29	2.05
Social sustainability	0.05	0.06	0.11	0.07	0.03	0.33
Environmental sustainability	0.05	0.06	0.15	0.21	0.10	0.57

Source: calculations by the authors.

Table A2. Results of assessment of relative importance of investment sustainability criteria.

Criteria	Commissioning Time	UTC	EMV	Expenditure on the Geological Exploration Program
Commissioning time	1/1	1/3	1/4	1/2
UTC (Unit Total Cost)	3/1	1/1	1/2	1/1
EMV (Expected Monetary Value)	4/1	2/1	1/1	3/1
Expenditure on the geological exploration program	2/1	1/1	1/3	1/1
Amount	10.00	4.33	2.08	5.50

Source: calculations by the authors.

Table A3. Results of assessment of relative importance of technological sustainability criteria.

Criteria	Technological Possibility of Project Implementation	EU and US Sanctions	Oil and Gas Field Complexity Category
Technological possibility of project implementation	1/1	1/7	1/2
EU and US sanctions	7/1	1/1	2/1
Oil and gas field complexity category	2/1	$\frac{1}{2}$	1/1
Amount	10.00	1.33	3.50

Source: calculations by the authors.

Table A4. Results of the assessment of the relative importance of the geological sustainability criteria.

Criteria	Potential for Accumulated Production	Success Evaluation	Difference in Accumulated Production P10/P50	Geological Exploration
Potential for accumulated production	1/1	1/2	1/1	$\frac{1}{2}$
Success evaluation P = (Extractable resources of the entity—minimum required resource size)/Extractable resources of the entity × gCOS × 100	2/1	1/1	1/2	1/3
Minimization of difference on accumulated production P10/P50	1/1	2/1	1/1	1/3
Geological exploration	2/1	3/1	3/1	1/1
Amount	6.00	6.50	5.5	2.16

Source: calculations by the authors.

Table A5. Results of assessment of relative importance of social sustainability criteria.

Criteria	New Jobs	Inflow of Highly Qualified Staff into the Project from Other Companies	Growth of Competencies of Company Employees Implementing the Project	Mechanisms for Feedback from Public Organizations and Regional Management Structures
New jobs	1/1	1/3	1/4	1/1
Inflow of highly qualified staff into the project from other companies	3/1	1/1	1/2	1/1
Growth of competencies of company employees implementing the project	4/1	2/1	1/1	1/1
Mechanisms for feedback from public organizations and regional management structures	1/1	1/1	1/1	1/1
Amount	9.00	4.33	2.75	4.00

Source: calculations by the authors.

Table A6. Results of the assessment of the relative importance of environmental sustainability criteria.

Criteria	Reliable oil Spill Response Technology	Preservation of Marine Ecosystems and Biodiversity	Minimization of CO_2 Emissions during Extraction and Transportation	Creation of Additional Insurance Funds of a Financial Nature
Reliable oil spill response technology	1/1	1/3	1/1	2/1
Preservation of marine ecosystems and biodiversity	3/1	1/1	3/1	2/1
Minimization of CO_2 emissions during extraction and transportation	1/1	1/3	1/1	$\frac{1}{2}$
Creation of additional insurance funds of a financial nature	1/2	$\frac{1}{2}$	2/1	1/1
Amount	5.50	2.17	7.00	5.50

Source: calculations by the authors.

Table A7. Results of a normalized assessment of the relative importance of the investment sustainability criteria.

Criteria	Commissioning Time	UTC	EMV	Expenditure on the Geological Exploration Program	Amount
Commissioning time	0.10	0.08	0.12	0.09	0.39
UTC (Unit Total Cost)	0.30	0.23	0.24	0.18	0.95
EMV (Expected Monetary Value)	0.40	0.46	0.48	0.55	1.89
Expenditure on the geological exploration program	0.20	0.23	0.16	0.18	0.77

Source: calculations by the authors.

Table A8. Results of a normalized assessment of the relative importance of technological sustainability criteria.

Criteria	Technological Possibility of Project Implementation	EU and US Sanctions	Oil and Gas Field Complexity Category	Amount
Technological possibility of project implementation	0.55	0.40	0.67	0.35
EU and US sanctions	0.27	0.20	0.11	2.02
Oil and gas field complexity category	0.18	0.40	0.22	0.86

Source: calculations by the authors.

Table A9. Results of a normalized assessment of the relative importance of the geological sustainability criteria.

Criteria	Potential for Accumulated Production	Success Evaluation	Difference in Accumulated Production P10/P50	Geological Exploration	Amount
Potential for accumulated production	0.17	0.08	0.18	0.23	0.66
Success evaluation P = (Extractable resources of the entity—minimum required resource size)/ Extractable resources of the entity × gCOS × 100	0.33	0.15	0.09	0.15	0.73
Difference in accumulated production P10/P50	0.17	0.31	0.18	0.15	0.81
Geological exploration	0.33	0.46	0.55	0.46	1.80

Source: calculations by the authors.

Table A10. Results of a normalized assessment of the relative importance of the social sustainability criteria.

Criteria	New Jobs	Inflow of Highly Qualified Staff into the Project from Other Companies	Growth of Competencies of Company Employees Implementing the Project	Mechanisms for Feedback from Public Organizations by Regional Management Structures	Amount
New jobs	0.18	0.15	0.14	0.36	0.84
Inflow of highly qualified staff into the project from other companies	0.55	0.46	0.43	0.36	1.80
Growth of competencies of company employees implementing the project	0.18	0.15	0.14	0.09	0.57
Mechanisms for feedback from public organizations by regional structures	0.09	0.23	0.29	0.18	0.79

Source: calculations by the authors.

Table A11. Results of normalized assessment of the relative importance of environmental sustainability criteria.

Criteria	Reliable Oil Spill Response Technology	Preservation of Marine Ecosystems and Biodiversity	Minimization of CO_2 Emissions during Extraction and Transportation	Creation of Additional Insurance Funds of a Financial Nature	Amount
Reliable oil spill response technology	0.11	0.08	0.09	0.25	0.53
Preservation of marine ecosystems and biodiversity	0.33	0.23	0.18	0.25	1.00
Minimization of CO_2 emissions during extraction and transportation	0.44	0.46	0.36	0.25	1.52
Creation of additional insurance funds of a financial nature	0.11	0.23	0.36	0.25	0.96

Source: calculations by the authors.

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Article

Sustainable Development of Oil and Gas Potential of the Arctic and Its Shelf Zone: The Role of Innovations

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Abstract: Currently, the Russian oil and gas industry is characterized by significant reserves depletion and the late stage of development of most fields. At the same time, new fields that are brought into industrial development, in the majority of cases, have hard-to-recover reserves. Furthermore, most prospective oil and gas deposits are located in the Arctic and its offshore territories and their development is much more complicated due to regional peculiarities. This substantiates the necessity of a special approach to the development of the oil and gas potential of the Arctic, based on innovation. The goal of the paper is to reveal the role of innovation activity in the sustainable development of the oil and gas potential in the Arctic and its offshore zone. The paper briefly presents the main urgent factors of Arctic development, which highlight the necessity of innovation for its sustainability. Then, it introduces the methods used for the research: the Innovation Policy Road mapping (IPRM) method in accordance with Sustainable Development Goals (SDGs) concept for clarifying how innovations will lead to sustainable development. In terms of results, this paper presents an innovation policy roadmap for the sustainable development of oil and gas resources of the Russian Arctic and its shelf zone and identifies the role of innovation within this development.

Keywords: innovations; sustainable development; hydrocarbon resources; Arctic; oil and gas potential; offshore oil and gas fields

1. Introduction

The Russian Arctic is a unique region with significant resources, great potential and strategic importance for Russia due to its unique mineral resource base (especially oil and gas deposits), promising ways to develop logistics infrastructure, and other factors. About 12% of Russia's territory is located beyond the Arctic Circle [1] and about 12–15% of the country's gross domestic product is created in the Arctic zone and it provides about a quarter of exports [2]. Provided the intensive and effective development of this region, especially the offshore zone, development of which requires a special approach with innovation technologies and proper skills, Russia can increase its resource potential several times, which will lead to an increase in the competitiveness of the Russian economy at the global level.

The accelerating climate change and altering accessibility to valuable minerals has affected expectations for a growing supply of northern resources globally. Plans for Arctic resource extraction are often considered as a vehicle for local economic development, which is reflected in the development strategies issued in Russia, Greenland, Canadian Nunavut, or Alaska [1].

The distribution of undiscovered hydrocarbon reserves between Arctic countries is presented in Figure 1 [2].

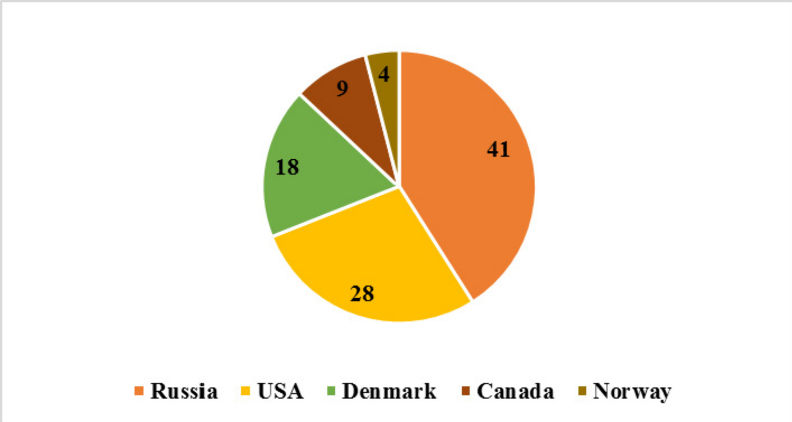

Figure 1. Distribution of undiscovered oil reserves between the Arctic countries, %.

The oil and gas complex of the Russian Federation is a large-scale unit of the national economy and the most important sphere of its resource-innovative development. A quarter of Russia's oil and gas condensate reserves and more than 70% of gas reserves (their cost is more than $20 trillion [3]) are concentrated in the Arctic zone of Russia and about 83% of gas and 12% of oil is produced there; however, its raw material potential is not fully developed. The largest oil and gas basins in the Arctic are the East Barents, South Kara, Laptev, East Siberian and Chukotka. Russia is developing Arctic hydrocarbon deposits on the Kola Peninsula, in Norilsk, in the northern regions of Western Siberia. The Nenets Autonomous district is an important center of oil production, while Yamal has become a center of gas production.

Twenty six oil and gas fields have been discovered on the Arctic shelf, seven of which are ready for development [4]. The deposits are located in the waters of three seas: the Barents, Pechora and Kara seas with total recoverable reserves of oil of about 0.6 billion tons, gas—8.5 trillion cubic meters [4].

The production of hydrocarbons is expected to grow in the near future. The planned volumes of production for Prirazlomnoye field—about 5 million tons (up to 2025). It is expected that production will start at the Dolginsky field (up to 2030) and at 1–2 more offshore fields. Besides at least 10 operating license areas for the development of hydrocarbons are located in the Pechora Sea (total recoverable resources are about 600 million tons of oil and 161 billion cubic meters of gas). At the same time, most of the license areas contain mainly oil deposits [5].

However, development of these resources is characterized by a number of obstacles, the main of which are the following [4]: high cost of exploration work, especially drilling exploration wells (several hundred million dollars at sea depths more than 1000 m); lack of a technologically simple alternative to traditional well drilling methods; and ineffectiveness of existing systems for collecting, preparing and transporting extracted products, etc.

Development of such oil and gas potential characterized by hard-to-recover hydrocarbons at great depths, shelf seas and the Arctic ocean, exploitation of oil deposits in the later stages of development, and the transportation of oil and gas across large distances through pipelines require developed infrastructure, qualified personnel and significant innovation potential. However, innovative development of the region is affected by such negative factors as the following [2]: undeveloped infrastructure of the Arctic zone (transport, information and telecommunication, market, etc.); low profitability of mining operations caused by the absence of developed infrastructure and developed power energy systems; the declarative character of laws and regulations and weak control over the implementation of the state strategies and programs; and imbalance in economic and innovative development between the separate Arctic territories and regions, etc.

A number of challenges of innovative development of the Arctic zone are connected with the absence of a systematic approach to the innovation infrastructure [6].

Despite that, the natural environment of the Arctic, including its shelf, is characterized by increased terms of restoration of the eco-balance due to man-made impacts. The main climatic characteristics of the region that complicate development of oil and gas potential in the Arctic zone are the following [4]: oil transportation in difficult natural and climatic conditions; difficult meteorological, temperature and hydrological conditions; difficult ice situation; extremely difficult wind regime; difficult bottom topography; high water depth in the presence of ice loads; ice period about 7–8 months, etc.

It should also be noted that Russian oil and gas companies are coming out of the period of low cost of oil production. The cost of production at new fields is 2–3 times higher than in traditional territories [7]. The Russian oil and gas industry is currently not sufficiently innovative in technological development and management [7], while the world's leading oil and gas companies invest in the development of high-tech technologies for the development of oil and gas deposits, which makes it possible to justify cost-effective ways to develop hard-to-recover hydrocarbon reserves. Therefore, innovations in the oil and gas industry also promote rational use of mineral resources, ensure the sustainable development of the region and increase the company's revenues.

The development of the Arctic zone of Russia is a priority task for the coming decades according to national policy [8,9]. The main national interests and the main directions of implementation of the state policy of the Russian Federation in the Arctic are presented in Table 1.

Table 1. National priorities in Russian Arctic development.

The Main National Interests of the Russian Federation in the Arctic	The Main Directions of Implementation of the State Policy of the Russian Federation in the Arctic
(a) Ensuring the sovereignty and territorial integrity of the Russian Federation; (b) Preserving the Arctic as a territory of peace, stability and mutually beneficial partnership; (c) Ensuring a high quality of life and well-being of the population of the Arctic zone of the Russian Federation; (d) Development of the Arctic zone of the Russian Federation as a strategic resource base and its rational use in order to accelerate the economic growth of the Russian Federation; (e) Development of the Northern sea route as a competitive national transport communication zone of the Russian Federation on the world market; (f) Environmental protection in the Arctic, protection of the native habitat and traditional way of life of indigenous small-numbered peoples living on the territory of the Arctic zone of the Russian Federation.	(a) Social and economic development of the Arctic zone of the Russian Federation, as well as development of its infrastructure; (b) Development of science and technology for the development of the Arctic; (c) Environmental protection and environmental safety; (d) Development of international cooperation; (e) Ensuring the protection of the population and territories of the Arctic zone of the Russian Federation from natural and man-made emergencies; (f) Ensuring public safety in the Arctic zone of the Russian Federation; (g) Ensuring the military security of the Russian Federation; (h) Protection of the state border of the Russian Federation.

It is expected that the strategy for the development of the Russian Arctic zone until 2035 will be approved soon. According to the draft of this document prepared by the Ministry of Eastern Development of Russia, by 2030 the share of oil produced in the Arctic should reach 22% of the total oil production in Russia, and by 2035—25% [9].

As it is observed from national interests and the situation in the oil and gas industry, the sustainable development of oil and gas potential in the Arctic and its shelf is a very urgent research and industrial issue. One of the most important aspects of the Arctic zone's sustainable development is an environmental issue. The importance of ecological as well as social aspects for sustainable development of the Arctic region cannot be overestimated [6,10]. Innovative development of the region in an ecological aspect will help to save ecosystems of the important strategic region of the Russian Federation for the further effective and sustainable development of the country [6].

In order to achieve these goals, it is necessary to develop a new approach to innovation activity in the Arctic zone for sustainable development of its resources. This paper aimed at defining the role of innovation in the sustainable development of oil and gas potential in the Russian Arctic and at the creation of an innovation policy roadmap for this purpose.

According to the purpose of this paper, we conducted an academic literature review of the following aspects: we track the connection between sustainability and innovation in the academic literature, study the role of innovation in the sustainable development of resources, study the innovation process in resource based industries, and study the concept of Sustainable Development Goals (SDGs), perspectives and problems of the Arctic and the necessity of an innovation approach, as well as the methodology of producing an innovation policy roadmap.

Many studies show the critical connection between innovation and sustainability. Innovation and sustainability create a critical link in the achievement of environmental, economic and social development [11–13]. Technological innovations are considered as an important element for sustainable development [11] and are recognized as a key factor of success for the development of society and the long-term survival of companies [14]. Some authors suppose that technological innovation causes the economic, environmental and social dimensions of sustainable development only for high income countries [15]. However, at the same time a very urgent issue remains—how to create innovations and remain economically profitable, ecologically sustainable and socially responsible [14].

Some studies underline the importance of innovation for sustainable development and the achievement of SDGs [16,17]. The Sustainable Development Goals (SDGs) are a collection of 17 interrelated goals, the achievement of which represents sustainable development [18]. They cover all aspects of sustainable development [19] and were introduced in order to understand sustainability in a more detailed and universally acceptable way [20]. Furthermore, private companies are the main factor in providing their achievement [20]. In this context, SDGs direct companies towards operating in sustainable way. At the same time, a very urgent issue appears—how to connect global SDGs with local goals [21] and how to correlate them with companies' goals. Therefore, there are studies that investigate the contribution of different industries in SDGs' achievement [22,23]. For the purpose of our research, we paid more attention to contribution of mining in SDGs. The report "Mapping Mining to the Sustainable Development Goals: An Atlas" presents the interpretation of the concept of SDGs for the mining sector [23]. It represents how certain mining corporate practices on a global scale contribute to certain SDGs. Some authors suppose that such an approach will push the mining industry towards integrating its practices "within a broader sustainable development framework" [24].

1.1. Role of Innovations in Sustainable Development of Resources

Innovation plays a key role in addressing mining challenges [25,26]. Mineral resources are key to the development of society [27]. Mineral resource depletion and the complication of extraction conditions substantiates the importance of new technologies and the energy revolution for the further availability of resources. In addition to economic considerations, it is essential to reconcile mining activity with environmental protection and to allay the concerns of local populations [27]. Some researchers suppose that sustainability implies the equal presence of economic, social and environmental sustainability [28]. Furthermore, in order to attain environmental sustainability, consumption of the world's natural resources, such as materials, energy fuels, land, water, etc., needs to be at a sustainable rate. In order to achieve economic sustainability, businesses and countries need to use their resources efficiently and responsibly. Social sustainability comes when any social system achieves good social well-being [28].

At the same time, there is a question in the research community—is the use of non-renewable resources sustainable? It depends critically on information that is unavailable to contemporary observers [29,30]. It could, however, be available soon due to future technological innovations.

In the context of the innovative development of the regional mineral complex, it is necessary to pay attention to the existing mining, oil and gas companies and to intensify the attracting of investments, the upgrading of equipment, the attracting of highly qualified personnel, etc. [6]. Some authors pay attention to innovations in the oil and gas industry [31] and suggest that an open innovation model can facilitate the process of responding to specific industry threats (for example, environmental and social pressure) [32,33] as well as study barriers that interrupt the innovation process in the oil industry [34].

1.2. Problems of Arctic Development

Much literature covers the perspectives and problems of the Arctic and the necessity of an innovation approach. Most all of them underline the importance of innovations for Arctic development as well as emphasize the necessity of environmental and social aspects in Arctic development [35–39]. It is substantiated that Russia obtains great resources and influence in the Arctic, but at the same time the Russian economy is not efficient enough and its commitment to sustainability (especially in Arctic development) might become more significant [35]. Despite the fact that hydrocarbon resources exploration employs millions of people and plays an important role in the Russian economy, it is also potentially harmful and often leads to negative environmental and social consequences [35].

Hydrocarbon exploration of offshore areas is difficult due to harsh weather conditions, darkness, ice, icing, and large distances [37]. In many Arctic regions, the existing infrastructure is insufficient to permit an adequate response to pollution of hydrocarbon exploitation. Special environmental and ecological conditions demand innovation technologies and protocols [37]. The lack of infrastructure along the Arctic coastlines is also considered as a very big problem in the case of reaching the coastline by oil spill, as many locations cannot be reached by cleaning equipment from land [37].

Despite the considerable attractiveness of offshore projects, its implementation is accompanied by difficulties such as the harsh weather conditions, the difficult geology (sea oil and gas production), as well as a lack of necessary technologies and infrastructure, making these projects time consuming and capital intensive [38]. Some studies concern factors and conditions that influence hydrocarbon production in the Arctic [39], while others concentrated on risks that appear during offshore oil and gas field exploitation [40]. It is established that there is a disproportionally high risk for Arctic ecosystems and various species, ecosystems, and communities are adversely affected (including indigenous peoples) [40]. In addition, problems of low population density and underdevelopment of transport infrastructure and features of different Arctic regions are discussed in the literature [1].

The issue of Arctic shelf sustainable development is also discussed and it is revealed that an economic and socioecological approach to Arctic shelf sustainable development is the only acceptable approach [41]. It is suggested that sustainable development of the Arctic shelf should be directed to the creation of the centers for economic development (CED) (oil and gas business clusters) [41].

1.3. Innovation Policy Roadmap

As it was mentioned, the main problem of innovative Arctic development is an absence of systemicity. Some authors suggest that system failures are result of "a lack of linkage and fragmentation between innovation actors" [42]. In order to regularize and organize actors, processes and challenges, a process of policy design is recommended [43]. In this context, the Innovation Policy Roadmap (IPRM) is suggested for systematizing innovation processes by consolidating drivers of innovations, policies, need for sectoral development as well as key enablers [42].

As for implementation of the IPRM as an instrument of policy-making for the Arctic, Hintsala et al. suggest the general strategic roadmap for Finland in the context of developing Arctic competences [36], but it does not consider issue of sustainable development of oil and gas potential.

Thus, analysis of previous studies revealed that there is no literature devoted to investigation of the contribution of innovation in the Arctic zone in SDGs' achievement as well as providing an innovation policy roadmap for the sustainable development of the oil and gas potential of the Russian Arctic zone (including the shelf zone). This paper is going to fill this gap and contribute to the innovation literature and literature concerning sustainable development of oil and gas resources by resolving two key issues: tracking the role and contribution of innovations in sustainable development in the context of achieving SDGs and the usage of the IPRM as an instrument for identification of the main aspects of sustainable development or Russian Arctic oil and gas potential.

2. Materials and Methods

In order to reveal the role of innovations, we use IPRM in accordance with SDGs for clarifying how innovations will lead to sustainable development.

IPRM method suggests combining two frameworks—the systemic transformation roadmap and technology road mapping [43]. It integrates analysis of social, environmental, industrial and other aspects in policy practice that arise from technological development, as well as present actors involved in the process, and facilitates the creation of a common vision as the basis of innovation policy [36,44]. Different approaches suggest different elements [36,43,44]; the general framework of the IPRM is presented in Figure 2.

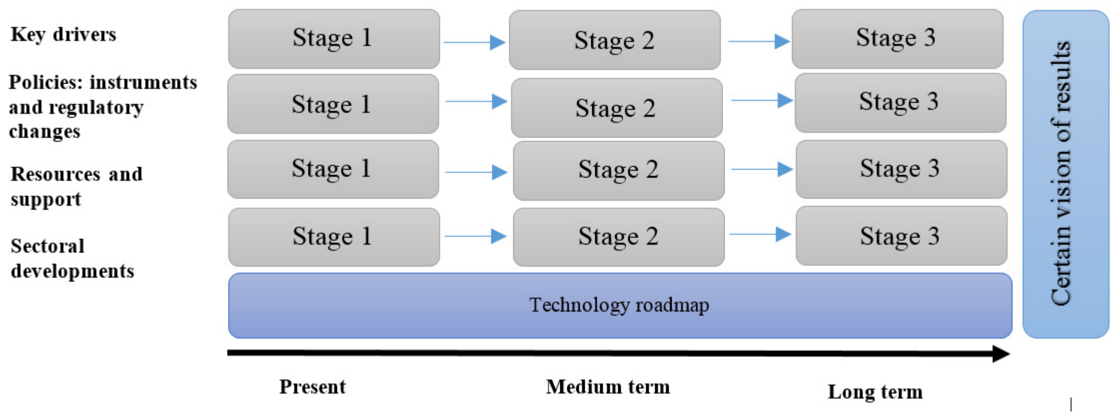

Figure 2. Framework for innovation policy roadmap creation.

The IPRM method shows how to achieve a certain vision that reflects the planned results. In order to reflect the results of sustainable development of oil and gas potential of the Arctic and the shelf zone, we adopt the concept of SDGs.

The concept of SDGs suggests the following goals—goal 1: No Poverty; goal 2: Zero Hunger; goal 3: Good Health and Well-being; goal 4: Quality Education; goal 5: Gender Equality; goal 6: Clean Water and Sanitation; goal 7: Affordable and Clean Energy; goal 8: Decent Work and Economic Growth; goal 9: Industry, Innovation and Infrastructure; goal 10: Reduced Inequality; goal 11: Sustainable Cities and Communities; goal 12: Responsible Consumption and Production; goal 13: Climate Action; goal 14: Life Below Water; goal 15: Life on Land; goal 16: Peace, Justice and Strong Institutions; goal 17: Partnerships to achieve the Goal [18].

The report "Mapping Mining to the Sustainable Development Goals: An Atlas" says that mining is a very urgent and global industry, which often located in distant, ecologically fragile and not developed areas that may include many indigenous lands and territories. It is totally concerned with the development of the oil and gas potential of the Arctic zone, especially its shelf territories. While mining is managed appropriately, it can create jobs, promote innovation and bring investment and infrastructure, even in changing environments, for a long-time. However, when managed poorly, mining can also lead to environmental degradation, displaced populations, inequality and increased conflict, among other challenges [23]. Mining activities have great impacts on land, water, climate, flora, fauna and people.

Atlas tracks the connection between mining and the SDGs by using examples of good practice in the industry and existing knowledge and resources in sustainable development that could make useful contributions to the SDGs in each sphere (Figure 3).

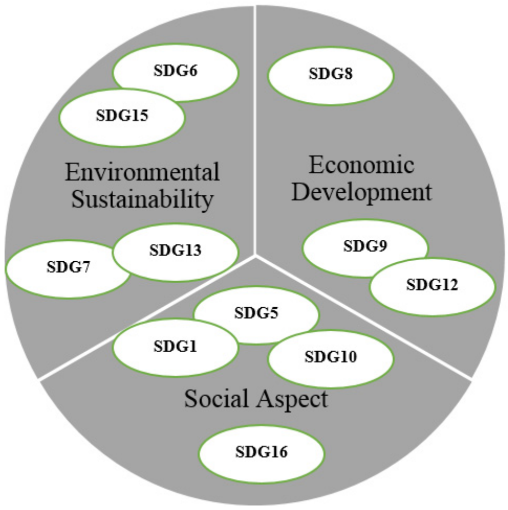

Figure 3. Sustainable development goals in mining according to [23].

Mining has a significant impact on local communities by bringing economic opportunities, as well as challenges relating to livelihoods and human rights. Mining generates significant revenues through taxes, royalties and dividends for governments to invest in economic and social development, in addition to opportunities for jobs and business locally [23]. As for economic development—mining has great impact on economic development and growth at the local, regional and even national levels.

3. Results and Discussion

We adopt a SDGs approach to Arctic conditions and oil and gas exploration on its territory and the territory of the Arctic shelf. We analyze and select SDGs that could be achieved by using innovations for development of oil and gas potential in the Arctic. This approach is a basis for revealing the role of innovations in SDGs' achievement and therefore in sustainable development of oil and gas potential of the Arctic and its shelf zone. We reveal enabling innovative technologies using the adopted SDGs' concept in order to track the contribution of innovations in sustainable development of oil and gas potential of the Russian Arctic zone (including the shelf zone).

Due to the threats that may appear during hydrocarbon production on the shelf (accidental oil spills; emergency emissions into the atmosphere; acceleration of global warming, ice melting, and extinction of rare animal species), significant attention should be paid to saving ecosystems under water. According to the features of oil and gas extraction on the shelf zone, SDG14—Life below water—is of particular importance. The hard climate, Arctic ice, lack of any coastal and road infrastructure, and difficulties in the development of the shelf area substantiate the necessity of an innovative approach for shelf development (advanced technologies, such as ice machines that are capable of fully producing oil and gas on the Arctic shelf are the means that can provide this).

The Arctic infrastructure in Russian part is quite poor and requires further development [45]. Moreover, local communities have legal or traditional rights, therefore exploration and exploitation within their territories requires taking into account their interests. The projects on developing of hydrocarbon resource deposit must be evaluated, taking into account the social potential of the project [45]. In such circumstances, SDG11—Sustainable Cities and Communities—is urgent for the achievement of sustainable development of oil and gas potential in the Arctic.

The arctic region (and especially its shelf zone) is characterized by very difficult working conditions. The state strategy for the development of the Arctic requires the attraction of human resources because the current situation indicates the outflow of population from the northern regions [46]. Companies need to engage qualified personnel by themselves due to hard climatic conditions, a shortage of key infrastructural elements in the Arctic region and imperfection of the legislative norms and government programs to support personnel. However, for the sustainable development of the oil and gas potential of the region, it is necessary to ensure the well-being of personnel as well as the native population. The development of oil and gas resources as well as future shipping routes (due to global warming, the northern Siberian route reduces the distance between major ports [47]) create one of the most serious problems for circumpolar indigenous peoples and their lands [48]. Significant harm to indigenous peoples is caused by industrial companies as they exploit natural resources, the locations of which often coincide with the areas used for the traditional lifestyles and economic activities of aboriginal peoples [49]. Therefore, SDG3—Good Health and Well-being—needs to be included.

Despite that, the development of the Arctic region is impossible without cooperation at all levels and in all spheres. The more difficult the conditions for resources' exploration and extraction, the more scientific research and innovations are required [41]. The main goals of Russia in its Arctic policy are to utilize its natural resources, use the seas as a transportation infrastructure in Russia's interests, protect its ecosystems, and ensure that it remains a zone of peace and cooperation with other countries [6]. This is impossible without partnership and cooperation. Cooperation between states and subsoil users in the event of the discovery of a trans-boundary hydrocarbon deposit is extremely important [45]. The necessity of cooperation between oil and gas companies, interregional cooperation in the innovation sphere, and cooperation between research centers and private companies for the creation of adapted technologies [6] makes SDG17—Partnerships to achieve the Goal—very urgent for the sustainable development of oil and gas potential in the Arctic.

According to the specifics of oil and gas potential development as well as its influence on the region's development, we suppose that the following goals and their aspects should also be involved in our research (Figure 4).

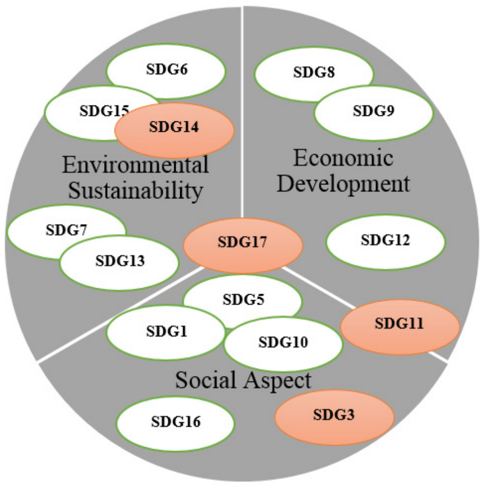

Figure 4. Sustainable development goals in the development of oil and gas potential of the Arctic and its shelf.

Using the IPRM method and the adopted SDGs concept, we created an innovation policy roadmap for the sustainable development of the Russian Arctic zone (Figure 5).

The roadmap consists of five elements. "Key drivers" are the global challenges that affect the development of oil and gas potential in the Arctic and support sustainable development goals related to this. The main global drivers are the increase in global energy demand, the depletion of traditional reserves, and climate change. As for drivers for Russia, the most significant is the strategic importance of the oil and gas industry for Russia as well as its national interests in the region. An increasing importance of environmental and social aspects also drives innovation activity for oil and gas potential development. The second element—"Policies: instruments and regulatory framework"—describes measures and changes that are needed to drive demand for innovative solutions, to provide economic incentives to industry, and to promote the implementation of innovations.

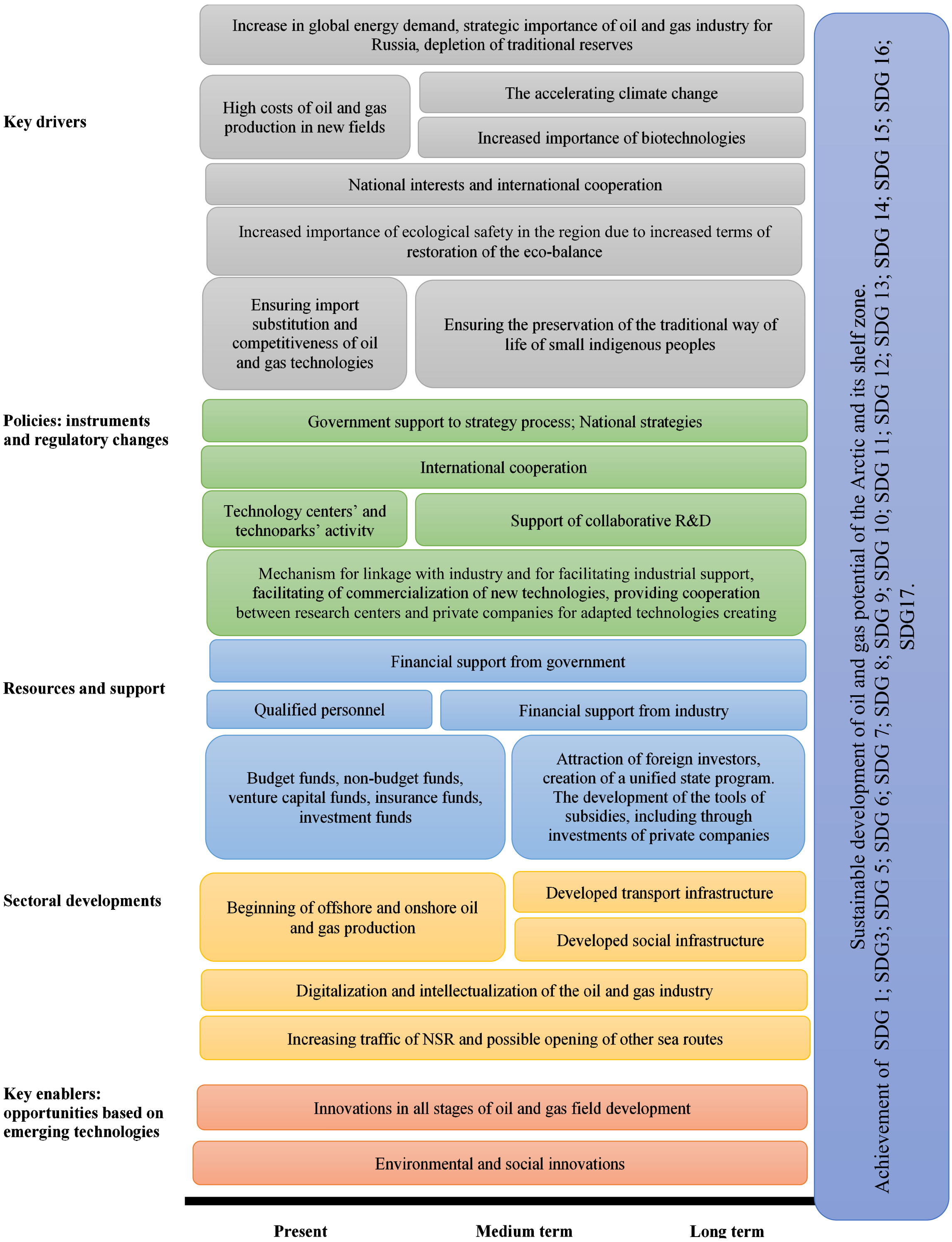

Figure 5. Innovation policy roadmap for sustainable development of oil and gas potential of the Arctic and its shelf zone.

The resources and support section provides information on which resources are needed to facilitate the process of innovations' implementation, and their movement from laboratories or universities to the market.

Sectoral development describes economic, industrial, environmental and social activities in the Arctic that could influence innovation activity in both sides—to promote or to impede it. The beginning of offshore and onshore oil and gas production as well as the digitalization and intellectualization of the oil and gas industry are the main sectoral characteristics that need innovation activity. In the medium term and long term, this could be supported by developed infrastructure, but at present this issue remains unsolved.

Key enablers provide existing or projected innovation technologies that support the innovation process for the sustainable development of oil and gas potential in the Arctic and support SDGs. We provide innovation technologies on all stages of the oil and gas field's development, and pay attention to environmental and social innovations.

IPRM brought together actors, processes and drivers of innovation activity in the development of oil and gas resources of the Arctic and its territories. It is seen that drivers provide challenges for innovation that require the support of sectoral development trends and that are impossible to implement without structured policy and different kinds of support from the state and companies.

In our research, we investigated the role of innovation for sustainability in the development of oil and gas potential of Arctic and its shelf zone. Thus, we studied how innovation leads to sustainability according to the SDGs. We tracked the role of existing and projected technologically innovative decisions on different stages of the exploration and exploitation process in sustainable development of the Russian Arctic zone. We highlighted the following stages: prospecting and exploration of hydrocarbon deposits; drilling oil and gas wells; development of hydrocarbon deposits; and transportation and storage of hydrocarbons, and the logistics and sales of products of their processing. We also emphasized environmental and social innovations.

We present existing and projected innovative technologies and solutions for development of resources in the Arctic and its offshore territories and substantiate their role in providing sustainability according to the adopted SDGs concept. The results are presented in Table 2.

As the table shows, specific innovative technologies contribute now or could contribute in the future to the achievement of sustainable development goals that in its turn provides sustainable development of oil and gas potential of the Russian Arctic and its shelf territories.

Sustainable development of offshore oil and gas resources is impossible without innovations in all stages of the process. Innovative technologies in exploration could lead to sustainability in the environmental, social and economic aspects. Russian companies are already implementing some innovations in the Arctic. For example, Gazprom Neft, during the development of offshore oil and gas fields, uses ice-resistant platforms on which drilling and production wells are placed, as well as a system for the remote control of equipment at the mouths of underwater wells. To organize its supply, the company has created a unique logistics scheme for the year-round transportation of hydrocarbons. Its key elements are the Prirazlomnaya oil production platform, the Arctic Gate terminal, a reinforced ice-class tanker fleet, its own and engaged icebreakers, and a roadside transshipment complex [53]. The world's first digital management system for Arctic logistics, "Kapitan", created by Gazprom Neft specialists, ensures the efficiency and safety of operations.

Therefore, the main findings of the research are the following:

(1) Sustainable development of oil and gas in the Arctic zone (especially the shelf) is a very urgent industrial and research issue due to the strategic importance of Arctic reserves, environmental and social challenges on the one hand and the lack of a research basis for it on another;
(2) Sustainable development of oil and gas fields in the Arctic zone is impossible without an innovative approach and the implementation of innovation policy, which could be done using the IPRM method;
(3) Understanding the role of innovations in the sustainable development of oil and gas potential of the Arctic zone is possible due to the innovation policy roadmap as well as tracking the achievement of SDGs using innovations;
(4) The SDGs concept needs adaptation to the peculiarities of development of oil and gas potential of the Arctic;
(5) The combination of IPRM and the identified role of innovation provides the possibility to distribute resources or other types of support on urgent issues, projects, spheres or territories.

Table 2. Role of innovations in sustainable development of oil and gas potential of the Russian Arctic and its shelf zone.

Spheres	The Main Tools of Innovative Changes	Role for Sustainable Development of Russian Arctic oil and Gas Potential	Provided SDGs
Prospecting and exploration of hydrocarbon deposits	(a) New technologies of seismic exploration (taking into account opportunities of digital technologies): - Basin modeling of hydrocarbon systems, forecasting promising zones for hydrocarbon prospecting, assessment of geological and geophysical risks; - 4D seismic monitoring for hydrocarbon deposits' prospecting, clarifying the hydrodynamic model of hydrocarbon deposits, including aquatically using "streamer cable", bottom fiber optic systems; - Under-ice seismic exploration for hydrocarbon deposits' prospecting in the Arctic regions in conditions when it is impossible or economically unviable to carry out seismic exploration from land or from geophysical vessels; - Pilotless aerial vehicle for carrying out aero-geophysical research; (b) Digital modeling of the pore space structure of reservoir layers and caprocks of hydrocarbon deposits. (c) Technologies for studying and efficient operation of unconventional reservoirs.	- Obtaining reliable information about the deep structure of the subsoil, the structure of reservoir layers and caprocks of oil and gas layers that provide higher precision of the data for further extraction as well as for planning future projects; - Providing possibilities for further development of hard-to-recover resources and for more efficient use of natural resources; - Supplying oil and gas companies, the Russian Federation and its regions with hydrocarbon resources.	SDG1 SDG7 SDG8 SDG9 SDG12 SDG15
Drilling oil and gas wells	(a) Construction of multi-hole and directional wells; (b) High-strength drill bits; (c) Robotic drilling ships and platforms of a new generation, including those for work in the Arctic: geolocation technology; icebreaker assistance or icebreaking performance; drilling in deep water conditions; (d) Blowout-preventing drilling equipment, preventers in conditions of abnormally high and abnormally low reservoir pressures and at great depths in the World Ocean, including for work in the Arctic; (e) Energy efficient top drive drilling systems to increase the rate of drilling, and to drill structurally difficult wells and improve safety while drilling.	- Involvement of multilayer hydrocarbon fields in effective development, as well as reservoir layers at great depths or in difficult geological conditions that provide extraction of hydrocarbons in condition of scarcity of existing resources; - Reducing the cost of drilling prospecting and exploration wells, as well as multi-hole and directional wells during the operation of reservoir layers in hydrocarbon fields.	SDG1 SDG3 SDG6 SDG7 SDG8 SDG9 SDG13 SDG14

Table 2. *Cont.*

Spheres	The Main Tools of Innovative Changes	Role for Sustainable Development of Russian Arctic oil and Gas Potential	Provided SDGs
Development of hydrocarbon deposits	(a) Digital modeling of hydrocarbon fields with predetermined technical and economic parameters: (b) Effective forecasting and use of methods to increase reservoir recovery at various stages of hydrocarbon production; (c) 4D, virtual and augmented reality technologies to support and make management decisions; - Reengineering of "mature" hydrocarbon fields; - Geological and technical measures to regulate the parameters of hydrocarbon field development in accordance with the target values for the hydrocarbon production volume; - Development technologies: fields of low-pressure gas (with low pressure in the reservoir); deposits of "rich" gas (with a high content of hydrocarbons from C3 and above); tight gas (shale); coalbed methane; gas hydrates of permafrost and deep-water depressions of the World Ocean; (d) Technologies and equipment for robotic subwater production complexes, umanned technologies for mobile subwater and production platforms in arctic conditions.	- Rational use of energy from the subsoil, formation of the ideology of the integrated development of hydrocarbon fields and their infrastructure; - Reducing the cost of hydrocarbon production, increasing the efficiency of field development; - Increasing the effective oil recovery factor; - Involvement of unconventional hydrocarbon deposits in the development; - Providing development offshore and marine resources.	SDG1 SDG6 SDG7 SDG8 SDG9 SDG12 SDG14 SDG15 SDG17
Transportation and storage of hydrocarbons, logistics and sales of products of their processing	(a) Highly efficient hydrocarbon pumping technologies: - Energy efficient units (pumps, compressors, drives) with high efficiency factor; - Specialized steels, composite and additive materials, 3D printing of finished products with high corrosion resistance and strength, for pipes and technological equipment for hydrocarbon transportation (including high pressure) and storage; - Autonomous power component, renewable and alternative energy sources for remote processing facilities of main and infield pipelines; (b) Intra-pipes diagnostics of main pipelines: - Devices for intra-pipes diagnostics with specified technical characteristics that are superior to world analogues—with the combination of X-ray and ultrasonic signals, and without the use of consumables; - Decrease in the energy consumption of intra-pipes "intelligent pigs" with a decrease in the spacing of sensors and an increase in the frequency of the "clearance" of the pipe metal for detecting longitudinal and transverse defects; - Monitoring and forecasting the development of defects, and the digital interpretation of data after diagnostics using digital transformation tools;	- Formation of a new transport and logistics infrastructure of the Far East, Eastern Siberia and the Arctic, taking into account the geological conditions of hydrocarbon fields and technical and economic analysis of possible ways of transporting hydrocarbons to markets, including the end consumer; - Creation of an environment of "technological trust" and effective interaction with the consumer based on multivariate forecasting and guaranteed satisfaction of demand for energy resources; - Extension of the maintenance-free service life, accident-free operation, maintainability of main pipelines and hydrocarbon storage facilities; - Reducing the cost of pumping hydrocarbons through pipelines; - Reduction in technological losses during transportation and storage of hydrocarbons and products of their processing; - Development of private bunkering, coastal and tanker fleets, including icebreaker vessels, and the necessary infrastructure.	SDG1 SDG3 SDG6 SDG7 SDG8 SDG9 SDG11 SDG12 SDG17

Table 2. *Cont.*

Spheres	The Main Tools of Innovative Changes	Role for Sustainable Development of Russian Arctic oil and Gas Potential	Provided SDGs
	(c) Technologies for protection from deposition in the main oil pipelines (from paraffins), and in gas pipelines (from hydrates); development of technologies for pumping gas in a two-phase or hydrated state; (d) Technologies and equipment for recovery of vapors of liquid hydrocarbons during their storage, loading onto tankers, railway operations, and small and medium-sized wholesale; (e) "Intelligent" devices for remote monitoring of transport infrastructure objects to control the stress–strain state (especially in hard-to-reach areas, for example, underwater, or in places of dangerous geological processes), outflows and prevention of unauthorized impact (space technologies, fiber-optic sensors, flying drones, etc.); (f) New technologies of welding production (especially for composite materials), quality control of welded joints.		
Environmental innovations	(a) Non-explosive signal sources in seismic exploration; (b) During drilling and hydraulic fracturing: - Underground utilization of drilling materials during the construction, operation and repair of oil and gas wells; - Closed systems for water treatment used to increase the recovery of layers; - Environmentally friendly chemistry—drilling fluids, biodegradable gels, inert materials for proppants; (c) Use of associated petroleum gas for own needs: - Energy and heat generation; - Production of aromatic hydrocarbons; - Low-tonnage liquefied natural gas and compressed natural gas facilities; (d) Nano-, composite and 3D materials, filter elements at all stages of production, processing, logistics of oil, oil products, gas; (e) Biotechnology: - Breeding of aquatic organisms (molluscs, scallops, sponges, fish) offshore to recreate biodiversity, purification and monitoring of water and bottom soil pollution with oil and oil products; - Sorbents and dispersants for the reclamation of land contaminated with oil and oil products, oil and oil product spills on land and sea, water and ice sludge purification in the Arctic regions; - To increase the layer recovery with the introduction of various bacteria or their formation in the layer itself;	- Formation of the image of energy companies as environmentally and socially responsible, providing measures to prevent man-made harm in all segments of oil and gas business, guaranteeing safety for life and health of citizens, and environment; - The use of renewable and alternative energy sources in all segments of oil and gas business to meet their own need for energy resources (including the introduction of the paradigm "oil and gas business is not a competitor, but a partner of renewable energy sources"), reducing the energy intensity of technological processes, reducing costs and increasing economic performance; - Elimination of anthropogenic impact, implementation of zero discharge technologies at oil and gas business facilities in natural areas with a special status, seas and oceans; - Development, implementation and independent control of transparent generally accepted methods for assessing anthropogenic and technogenic impact on the environment.	SDG3 SDG6 SDG7 SDG9 SDG11 SDG12 SDG13 SDG14 SDG15 SDG17

Table 2. *Cont.*

Spheres	The Main Tools of Innovative Changes	Role for Sustainable Development of Russian Arctic oil and Gas Potential	Provided SDGs
	(f) Technologies for the use of renewable energy sources (sun, wind, water) for generating energy for own needs and at remote technological facilities, carbon dioxide utilization processes, new energy distribution networks GTL (gas-to-liquid), CTL (coal-to-liquid), Power-to-Gas and Gas-to-Power. (g) Infrared technology for the early discovery of spills, both underwater and on the ocean surface, including infrared technology on a helicopter, an aircraft, and on a preparedness vessel that was optimized to deal with cold weather		
Social innovations	(a) Multi-stakeholder initiatives (MSI) with different aims, directions and organizational designs; (b) Local forums for community development and capacity building; (c) Creative approaches to service provision; (d) Providing community spaces and activities; (e) Creating of the social movement such as the Association of indigenous peoples of the North, Siberia and the Far East—the indigenous peoples of the Arctic zone of the Russian Federation; (f) Advanced practices of regional international cooperation in the Arctic with effective improvement of public administration at the level of local self-government bodies (municipalities).	- Protection of interests of indigenous people for providing social sustainability; - Creation of social infrastructure both for native habitants and for personnel; - Encouraging cooperation on different levels on issue of social infrastructure development in the Arctic and its shelf.	SDG3 SDG8 SDG9 SDG11 SDG16 SDG17

Source: authors' own compilation using [37,50–52].

The results of the paper do not contradict previous studies [31–41] that underline the importance of innovation for resource-based industries and the strategic importance of the Arctic for Russia, and substantiate the necessity of sustainable development of its resources, but supplement them and contribute to research literature by providing the possibility to track the contribution of innovations to sustainable development through achieving SDGs. As for practical implementation, the results of the research could be used by government policy makers, by oil and gas companies during strategy formation, as well as by state and private R&D companies.

The main assumptions of the research are the following: in the research we concentrated on Arctic territories of the Russian Federation and considered the peculiarities of Russian oil and gas potential, so the results for other countries could be interpreted in accordance with its features and characteristics; we did not consider specific indicators or quantitative measures of SDGs' achievement; we used open information sources.

As for future research directions, we could focus on innovative activity in different Arctic regions as well as providing an innovation policy roadmap not only for Russia, but also for all actors in the Arctic territory.

4. Conclusions

The Arctic region of Russia, including its shelf, is one of the most attractive and promising territories in terms of hydrocarbon production potential. The development of the Arctic is a high-tech and innovative process that determines the innovative development of a number of industries and territories.

Currently, there are more than 10 states operating on the shelf that already have technologies for the exploration and production of hydrocarbons. Therefore, effective development of the shelf by Russia is necessary in order not to increase the technological gap and to promote the sustainable development of offshore resources on the Arctic shelf aimed at economic profit, ecological sustainability and social responsibility. An innovative approach needs to be implemented in order to achieve this. According that background and the purpose of the research, the following results were obtained:

(1) Substantiation of strategic importance of sustainable development of Russian Arctic offshore oil and resources due to its great potential on the one hand and depletion of existing fields and scarcity of resources on the other.
(2) Identification of the main challenges that justify the necessity of an innovation approach for the sustainable development of Russian Arctic oil and gas potential, which is supported by national interests in this sphere.
(3) Adaptation of the SDGs concept to the issue of sustainable development of oil and gas potential of the Arctic and its shelf and the provision of a list of SDGs that are involved in this process and provide sustainability in economic, social and environmental aspects.
(4) Innovation policy roadmap for the sustainable development of the oil and gas potential of the Arctic and its shelf zone that presents actors involved in the process and facilitates the creation of a common vision for the basis of innovation policy as well as providing analysis of social, environmental, industrial and other aspects in policy practice that arise from technological development.
(5) Determining the role of innovation for the achievement of SDGs and for the sustainable development of the oil and gas potential of the Arctic and its shelf zone using IPRM together with the adopted SDGs concept.

Understanding the aforementioned role makes it possible to manage the innovation process in the Arctic resources' development depending on what goals and needs are extremely important or what problems need to be solved in the near future. For an effective innovation, development and implementation process, it is important to use the scientific potential of the Russian Federation with the involvement of leading foreign designers, acquire innovation technologies and production licenses, and involve leading foreign companies as subcontractors or on a joint basis. It is necessary to accumulate the organizational, technological and financial potential of the state and leading Russian oil and gas companies to coordinate and develop new technologies and designs, as well as to implement the program of exploration and development of mineral resources on the Arctic continental shelf, which will provide sustainable development for the region.

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Issue of Accumulation and Redistribution of Oil and Gas Rental Income in the Context of Exhaustible Natural Resources in Arctic Zone of Russian Federation

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Abstract: The significant resource potential of the Arctic has attracted the attention of its adjacent countries and extra-regional states. The mineral and raw material base of the Arctic Zone of the Russian Federation (AZRF) comprises a wide range of minerals. However, due to its hydrocarbon reserves, the Arctic is considered to be the most important geopolitical and geo-economic macro-region for Russia. A significant portion of the Arctic hydrocarbons (about 19%) is concentrated in the territory of Russia's shelf. The extraction of Arctic marine oil and gas resources and ensuring the sustainability of the Russian energy complex depend significantly on the level of Arctic development. Thus, the pace and quality of the development of AZRF are strategically important to ensure the national interests of the country. It has been proven that the implementation of the state program for AZRF development and strategic plans of the largest companies operating in the region consolidate the raw material nature of AZRF development. Rent becomes the main form of income. This article addresses the main directions of the region's development and the factors that prevent a high level of industrialization, which increase attention to the withdrawal and redistribution of rental income. The article considers the Russian and foreign experiences of withdrawal and redistribution of oil and gas rental income, and analyzes the level of socio-economic development of AZRF. The authors suggest a methodology for assessing the impact of a country's area and population size on the ability to achieve a high income due to hydrocarbons. The authors also explain the principles of rental income redistribution in the region as a basis for improving the level of AZRF's socio-economic development and as a condition for transition from the "colonial model" of development to the "sustainable development" model. The study results can be used to elaborate a mechanism for rental income redistribution in AZRF and state programs for the region's development.

Keywords: the Arctic Zone of the Russian Federation; oil and gas resources; Arctic shelf; rent; sustainable development

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1. Introduction

The Arctic is now a major attraction, not only to the near-Arctic states (Russia, the USA, Canada, Norway, and Denmark), but also to extra-regional states (China, Japan, India, etc.) due to its significant resource potential.

Russia, a leading country in hydrocarbon production, mines 83% of all produced gas and 12% of all produced oil in the Arctic zone [1]. The raw material base of the Russian oil and gas industry is characterized by the fact that large and highly profitable deposits are largely exhausted, and the most investment-attractive part of the subsoil use fund has been distributed (98.4% of oil and 97.45% of gas in A, B, C1 categories) [2]. Because production is naturally declining in traditional areas, oil and gas companies have to focus on zones with hard-to-recover reserves [3]. The exhaustion and deterioration of the raw material base of the oil and gas complex add strategic importance to the Arctic region.

Thus, the Arctic shelf territories could eventually become the main oil and gas producing region globally. In the structure of the initial total resources (ITR) of Russian's oil shelves (on 1 January 2018), accumulated production comprises 1%, reserves of the categories A + B1 + B2 + C1 + C2 comprise 8%, resources of the category D0 comprise 26%, and resources of the category D comprise 65%[1] (Figure 1) [2].

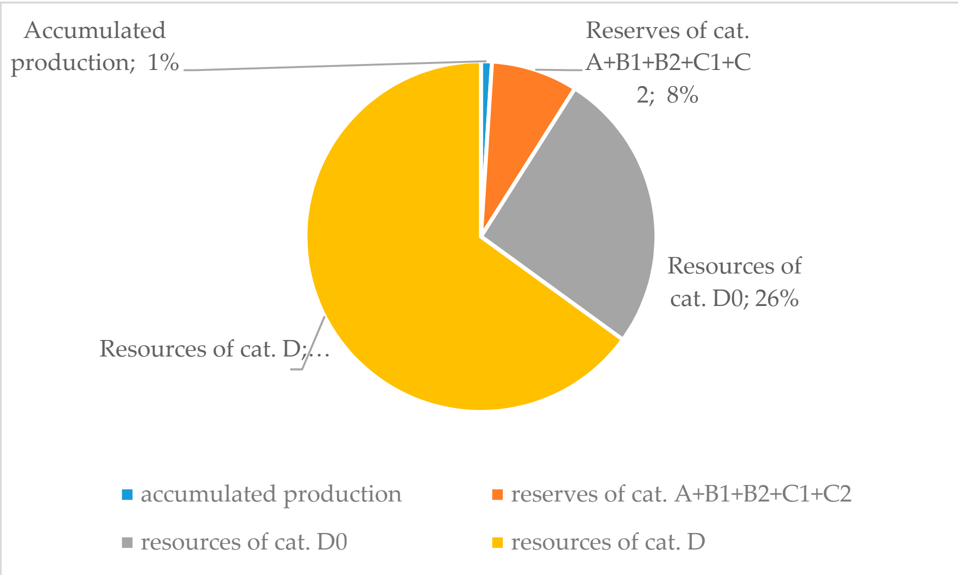

Figure 1. Structure of the initial total resources (ITR) of Russian's oil shelves (on 1 January 2018), %.

In the structure of initial total resources (ITR) of Russian's free gas shelves (on 1 January 2018), accumulated production accounts for 0.5%, reserves of the categories A + B1 + B2 + C1 + C2 for 12%, resources of the category D0 for 12%, and resources of the category D for 75.5% (Figure 2) [2].

In addition, AZRF plays an important role in ensuring military security. The region's logistical potential is growing, and global warming has led to the active development of the Northern Sea Route (NSR). Thus, AZRF has become not only the most important resource region, but also a geopolitical and geo-economic macro-region. Russia's presence in the region, the pace and quality of development of AZRF are of strategic importance to ensure the national interests of the country.

The possibility of developing Arctic offshore oil and gas resources largely determines the level and quality of the region's development.

"Basic Principles of Russian Federation State Policy in Arctic to 2035" [4] and strategic plans of the largest companies operating in the region consolidate the raw material nature of AZRF development. Rent becomes the main form of income. Mining companies have become systemically important for regions, where they are operating, as they have established a complex system of social and economic interests for businesses, the state, indigenous population, and society as a whole.

[1] According to the Order of the Ministry of Natural Resources and Environment of the Russian Federation as of 1 November 2013, No. 477 "On Approval of the Classification of Reserves of Oil and Combustible Gases", oil and gas reserves are subdivided by the extent of commercial development and by the degree of geological knowledge into the following categories: A (developing, drilled), B1 (developing, not drilled, known), B2 (developing, not drilled, estimated), C1 (known), and C2 (estimated). Oil, gas, and condensate reserves are subdivided by geological knowledge into the categories D0 (prepared) and D (localized, prospective, and expected).

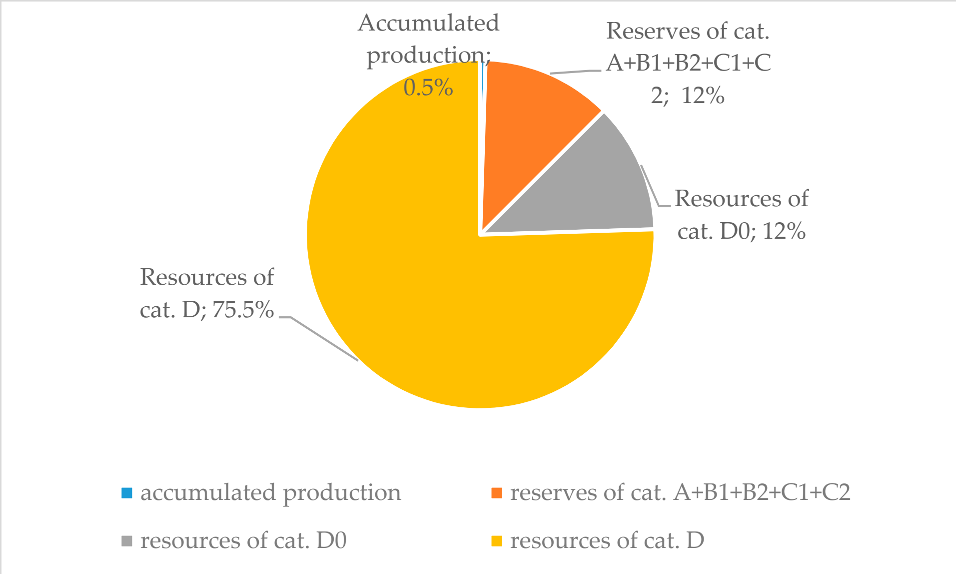

Figure 2. Structure of initial total resources (ITR) of Russian's free gas shelves (on 1 January 2018), %.

Intensification of industrial and transport development in AZRF will naturally lead to the growth of rental income, but it will not stay in the region. According to Article 9 of the Constitution of the Russian Federation "1. Land and other natural resources shall be used and protected in the Russian Federation as the basis for the life and activities of peoples living in the respective territory. 2. Land and other natural resources may be in private, state, municipal and other forms of property" [5].

The wording of the article rules may lead to different interpretations of natural resource use and management. For example, the idea that land and natural resources are the property of "the peoples of the respective territory." However, Article 9 refers to the protection and use of land and other natural resources as the basis for "lives and activities of peoples living in the respective territory." [5]. This does not mean that the right of ownership (ownership/disposal) belongs to the constituent entities of the Russian Federation. In this regard, according to the Law of the Russian Federation "On Subsoil Resources" adopted in 1992 [6], the subsoil resources are the state property and are under the joint competence of the Russian Federation and its constituent entities [7].

The issue of exhaustible natural resources and the raw material nature of AZRF development have increased the focus not only on the issues of withdrawal, but also on the redistribution of rental income. In the long term, the establishment of the raw material development model with full withdrawal of rental income will lead to exhaustion of the resource potential and will not allow creating "the future potential for meeting human needs and aspirations", which contradicts the concept of "sustainable development". (Sustainable development means a process of economic and social changes where the exploitation of natural resources, the investment direction, the direction of scientific and technological development, personal development and institutional changes are mutually compatible and strengthen the current and future capacities to meet human needs and aspirations.)

The aforesaid determines the relevance of the research and sets the following tasks: to analyze the directions of AZRF development; to assess the level of the region's socio-economic development; to consider the principles of rental income withdrawal and redistribution in Russia and the Arctic countries with successful experiences; to justify the principles of redistribution and use of rental income in order to improve the level of socio-economic development of AZRF and to transit to the "sustainable development" model in the region.

2. Materials and Methods

During the study of issues of accumulation and redistribution of oil and gas rental income under exhaustible natural resources in the Arctic zone of the Russian Federation, the authors used the following methods: economic–statistical, comparative and geographic, historical analysis; forecasting effort; method of analysis, comparison, and summarizing of available information about the implementation of public policy projects in the Arctic zone, strategies for the rent redistribution both in Russia and abroad. The authors conducted a thorough analysis of national and foreign periodicals, fundamental scientific materials, documents of ministries, official websites of companies and foundations engaged in the investigated issues.

The methods were chosen in accordance with the study objective: to justify the principles of rental income redistribution in AZRF that will allow improving the level of socio-economic development of AZRF, switching to the "sustainable development" model, and reducing inequality in regional development. The system of research methods allows studying the theoretical basis and history of issues, collecting data on the current state of the issue, observing the principles of objectivity and systematic research, as well as the principle of results reproducibility.

After the forced interruption period in the 1990s and early 2000s due to the difficult economic situation in Russia, research activities related to the Arctic have intensified in recent years [8–10]. The main reason for the increasing number of published materials is the strategic importance of the Arctic region. However, the elaboration of recommendations on how to improve the processes of rent withdrawal, assignment, and use in the mining industries requires further development taking into account both national and international experiences [11,12].

The following representatives of classical economics contributed greatly to the development of the theory of rent: Sir William Petty, James Anderson, Adam Smith, David Ricardo, John Stuart Mill, Karl Marx, and others; as well as physiocrats: François Quesnay and Anne Robert Jacques Turgot; neoclassicists and marginalism followers: Alfred Marshall, John Bates Clark, and others. The following Russian researchers studied issues of rent in mining industries: S. G. Strumilin [13], N. V. Volodomonov [14], A. S. Astakhov [15], V. P. Pakhomov [16], L. G. Khazanov [17], S. = A. = Bulat [18], D. S. Lvov [19], S. Yu. Glazyev [20], V. S. Nemchinov [21], N. N. Lukyanchikov [22], V. A. Meshcherov [23], Yu. V. Razovskiy [24], S. A. Kimmelman [25], V. K. Shkatov [26], V. T. Ryazanov [27], and others. Issues of oil and gas rent withdrawal were investigated in the works of A. E. Kontorovich [28], V. I. Nazarov [29], M. D. Belonin [30], A. N. Aleshin [31], and others.

The analysis of scientific and applied research and published materials has shown that it is important to improve distribution and allocation processes for rental income gained in AZRF. The scale and complexity of rental income redistribution are connected with property relations in the sphere of subsoil use. Subsoil resources are state property in Russia. So the state has the right to establish and control the system of rent relations. However, the level of socio-economic development of AZRF calls into question the existing principles of rental income withdrawal and redistribution.

Opinions about principles of rent withdrawal and assignment vary: either rent should be distributed among citizens and transferred to their personal accounts, or it should be withdrawn for the benefit of certain groups of the country population, or rent should be used centrally: to establish funds, etc., [32–37]. However, what method of rent redistribution is appropriate for Russia and its regions that have their own peculiarities? Many studies have been devoted to issues of rental income withdrawal. However, the peculiarities of AZRF and its level of socio-economic development require further studies of the principles of rental income redistribution and their adaptation to the regional conditions.

An important stage in justifying the principles of rental income redistribution and use is the analysis of the efficiency of hydrocarbon use in countries with the rent economy. The authors have put forward a hypothesis that the ability to achieve a high income due to hydrocarbons depends not only on the strength of social and political institutions, but is also largely determined by the area of a country and its population size. The authors propose the following analysis algorithm:

1. Select ten major countries producing oil and gas. Recalculate their oil and gas production into tonnes of a standard fuel in order to compare the figures.
2. Select countries funding sovereign wealth funds with hydrocarbon revenues from the list.
3. The authors propose to assess the impact of the area and the population size using an n-fold multiplicative model:

   $Ira = \frac{Q}{\sqrt[2]{S*N}}$, where
   Ira is the resource availability index.
   Q is hydrocarbon production in tonnes of a standard fuel.
   S is the area of a country in thousands of km^2.
   N is the population size in millions of people.

   The authors suppose that not only the population size but also a country's area should be taken into account while estimating a country's provision with hydrocarbons. If the provision is estimated via the ratio of production to the population (Q/N), the result is misrepresented, because countries with large areas have to maintain a large and power-consuming transport infrastructure and have larger production facilities. It leads to increasing local demand and consumption of power resources. As a result, export opportunities and rent income decline. So, the authors propose to consider a country's area for the correct estimation. *Ira* provides a generalized estimation of a country's provision with hydrocarbons. The lack of standards leads to the use of comparative analysis by country.
4. Countries are ranked by the Gross National Income (GNI) per capita (the purchasing power parity, PPP, $). The average GNI per capita is calculated for the selected countries. The countries are divided into two groups: with the GNI per capita above the average level and below it.
5. The performed calculations allow determining the *Ira* value required for the population to gain high incomes in countries possessing hydrocarbon reserves.

The analysis algorithm is shown in Figure 3.

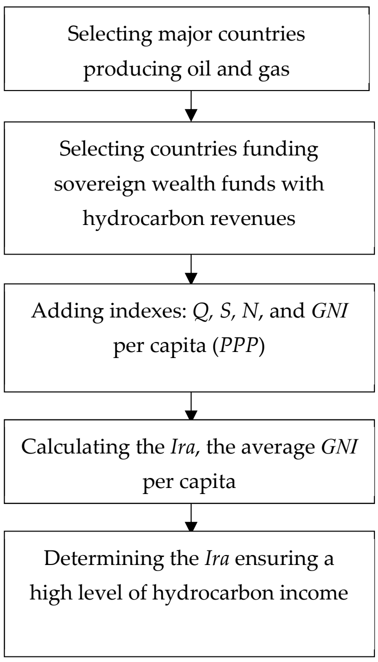

Figure 3. A flow chart of the methodology for assessing the impact of a country's area and its population size on the ability to achieve a high income due to hydrocarbons.

The proposed methodology allows analyzing if it is possible to conduct a state policy for raising the population's income via rent and to decide how rental income should be used and redistributed. Nevertheless, the authors' approach has some restrictions. Rent is a multidimensional category arising not only in case of execution of the ownership right to resource factors. Non-economic resources can also generate rent income, which leads to political rent, administrative rent, monopoly rent, etc. The proposed methodology can be used only to estimate a possible rise of income due to hydrocarbon reserves.

3. Results

On 5 March 2020, the President of Russia signed decree No. 164 "Basic Principles of Russian Federation State Policy in Arctic to 2035", which defined the state policy in the national security and protection of national interests of Russia in the Arctic zone. According to the Decree, acceleration of socio-economic development of AZRF is mainly connected with "the development of the Arctic zone of the Russian Federation as a strategic resource base" and "the development of the Northern Sea Route" (NSR) [4].

The current economic situation in the country and in the world, as well as the changing climate on Earth and in the Arctic region, have influenced the decisions of the Russian Government.

Global warming, the consequent melting of the Arctic ice, as well as implementation of projects to upgrade and broaden the fleet of nuclear-powered icebreakers have prolonged the navigation season and the possibility of cargo transportation by NSR. In 2019, freight transportation by NSR totaled 31.5 million tonnes [38]. According to AZRF's development strategy, the figure will amount to 80 million tonnes by 2024, to 120 million tonnes by 2030, and to 160 million tonnes by 2035. Today, mineral raw materials (oil, liquefied natural gas, gas condensate, and coal) account for 96% of cargoes transported by NSR. Olga Surikova, the head of Far East Practice, KPMG, supposes that "the situation will not change significantly by 2024" [39].

The AZRF's mineral and raw material base comprises a wide range of minerals: high-quality coal [40–43], iron, manganese, gold, nickel, copper, etc. However, due to hydrocarbon reserves [44,45], the Arctic is considered to be the most important geopolitical and geo-economic macro-region. A significant part of the Arctic hydrocarbons (about 19%) is concentrated in the territory of Russia's shelf. AZRF accounts for 25% of the country's oil reserves and for 70% of gas reserves [1].

Implementation of projects for the extraction of the Arctic hydrocarbons is impeded not only by traditional restrictions (severe natural and climatic conditions, underdeveloped industrial and logistics infrastructure, low density and uneven settlement of the population, etc.), but also by the geopolitical situation (sanctions imposed on offshore production), a decline in demand for hydrocarbons and as a result decreased prices connected with the COVID-19 pandemic. However, on 18 August 2020, at the meeting of the President of the Russian Federation V. Putin and the head of PJSC Rosneft Oil Company I. Sechin, they noted that "This situation will run its course sooner or later, and economic growth will resume both internationally and in Russia" [46]. This statement preserves the importance and role of AZRF in Russia's economy and in ensuring the country's geopolitical position.

At present, PJSC Rosneft Oil Company possesses most of the licenses for the development of offshore fields in the Russian Federation. The company considers continental shelf development to be a strategic area of the mineral resource base development. On 1 April 2019, at a meeting with Russian President V. Putin, the head of Rosneft I. Sechin said that the company planned to set up an Arctic cluster in order to ensure NSR loading and to produce up to 100 million tonnes of oil by 2030 [47]. Rosneft expects that "by 2050, the Arctic shelf will cover 20–30% of all Russian oil production" [48].

The close attention to the Arctic during the past decade, approval of the State Policy Framework (2008) and implementation of the AZRF Development Strategy have resulted in the intensification of industrial and transport development of the region and positive dynamics of the Gross Regional Product (GRP) (Table 1).

Table 1. Share of GRP produced in AZRF in the aggregate gross regional product of the Russian Federation's constituent regions, %.

	2014	2015	2016	2017	2018
Total for the Arctic zone of the Russian Federation	5.0	5.2	5.4	5.8	6.2

Source: [49].

However, today AZRF lags behind the average level in Russia in many socio-economic indicators, which is also confirmed by the depopulation process in territories. The resident population of the Arctic decreased 30% during 30 years (Table 2). Migration of the population from the Arctic regions occurs due to numerous reasons. People move to more favorable regions of the country, where climatic, socio-economic, cultural, and living conditions are better [50,51].

Table 2. Dynamics of the resident population of AZRF's overland territories (number of humans).

AZRF's Constituent Region	1989	2019	Total Population Decline (1989–2019), People	Total Population Decline (1989–2019), %
Arctic zone of the Russian Federation	**3,471,581**	**2,397,509**	**−1,074,072**	**−30.9**
Including: European part:	**2,349,490**	**1,551,461**	**−798,029**	**−34.0**
Murmansk region	1,164,586	748,056	−416,530	−35.8
Karelia Republic	82,141	41,605	−40,536	−49.3
Arkhangelsk region, excluding Nenets Autonomous Okrug	830,384	643,215	−187,169	−22.5
Nenets Autonomous Okrug	53,912	43,829	−10,083	−18.7
Komi Republic	218,467	74,756	−143,711	−65.8
Asian part:	**1,122,091**	**846,048**	**−276,043**	**−24.6**
Yamalo-Nenets Autonomous Okrug	494,844	541,479	46,635	+9.4
Krasnoyarsk region	379,430	228,943	−150,487	−39.7
Sakha Republic (Yakutia)	83,883	25,963	−57,920	−69.0
Chukotka Autonomous Okrug	163,934	49,663	−114,271	−69.7

Source: calculated by the authors considering data of [52,53].

At the same time, there is an extreme polarization of AZRF's economic space. According to the assessment of RIA Novosti based on the data of Rosstat, the largest average income in respect of the cost of a fixed set of goods and services is recorded in Yamalo-Nenets Autonomous Okrug. Another northern oil and gas region—Nenets Autonomous Okrug—ranks second (Table 3).

Table 3. AZRF region ranking by income of population.

Place in the Ranking of Russia's Regions	Region	Ratio of Median Income to the Cost of a Fixed Set of Goods and Services	Share of Population below the Poverty Line in 2019, %	Share of Population below the Extreme Poverty Line in 2019, %
1	Yamalo-Nenets Autonomous Okrug	3.11	5.6	0.8
2	Nenets Autonomous Okrug	2.92	9.5	1.5
4	Chukotka Autonomous Okrug	2.27	8.7	1.1
12	Murmansk region	1.92	10.8	0.9

Table 3. *Cont.*

Place in the Ranking of Russia's Regions	Region	Ratio of Median Income to the Cost of a Fixed Set of Goods and Services	Share of Population below the Poverty Line in 2019, %	Share of Population below the Extreme Poverty Line in 2019, %
15	Sakha Republic (Yakutia)	1.71	17.9	3.3
22	Komi Republic	1.62	15.5	2.2
29	Arkhangelsk region	1.56	12.7	1.4
41	Krasnoyarsk region	1.51	17.5	2.8
45	Karelia Republic	1.50	15.7	1.7

Source: compiled by the authors considering data of [54].

Yamalo-Nenets Autonomous Okrug and Nenets Autonomous Okrug differ from other regions outstripping Moscow (ranks third in the list) with a 20% gap [54]. It is connected with oil and gas production and the northern status of the regions. According to Table 3, other Arctic regions rank considerably lower. This fact demonstrates a high level of income differentiation between AZRF's regions and the Russian Federation in general.

The state program for AZRF development and strategies of the largest companies operating in the region aims at fulfilling the logistic (in the foreseeable future) and mineral (in the long-term) potential of the region, primarily hydrocarbons, making rent the main form of income.

Many studies have been devoted to rent as an economic category, to issues of its withdrawal and redistribution. The rent category has been developed for over 300 years, but even today there are many concepts and approaches. There are different types of rent: raw material (mining, land, forest, etc.), administrative, political, economic and others. Rent is the income of the resource owner; the resource supply is strictly limited and is in demand. It is unearned income (income not acquired through work) and occurs at the owner of the resource as a result of a certain situation and conditions of economic relations. The oil and gas industry features mining, price, and currency rents.

The mining rent consists of absolute (determined by the limit deposit with the worst conditions) and differential rent. The differential mining rent in its turn is divided into rent of the first order (occurs on the medium and the best deposits) and of the second-order (as a result of intensive management). Today, a method of quantitative determination of differential mining rent of the first and second orders does not exist, because practically it's impossible to distinguish the share in the total increase in income obtained due to the best natural characteristics of a deposit and the increase caused by investment factors. So a system of differentiated rent payments and benefits has been developed in the world practice [7].

The price and currency rents may arise as a result of an increase in the world oil prices (if domestic prices differ) and a decrease in the ruble exchange rate.

The following types of rent payments exist in oil and gas production: annual payments (rentals: for the right to explore for hydrocarbons, royalties: for the right to extract hydrocarbons); one-time payments (when certain events occur under the license). In modern Russia, royalties, contributions to the replacement of the mineral raw material base and excise taxes on oil and gas have been replaced with the Mineral Extraction Tax (MET) [55]. MET and export duties are the main instruments for the rent withdrawal from subsoil users. Another specific industry tax is the excise tax on petroleum products, but this value is added to the price and is actually paid by the consumer. It is worth mentioning that since 1 January 2019 MET has been replaced with the Added Income Tax (AIT) as an experiment for a number of fields in Siberia, Komi Republic, Nenets Autonomous Okrug, and the Caspian Sea. AIT is charged not on the gross figures (as MET) but depends on the profitability of a company's project.

The oil and gas industry is not only the main source of currency revenues, but also accounts for a significant part of the budget (Table 4).

Table 4. Extended government budget revenues from taxes and duties related to taxation of oil, gas and petroleum products in 2012–2018 (% of GDP).

	2012	2013	2014	2015	2016	2017	2018
Tax revenues and payments	**31.86**	**30.80**	**31.29**	**28.97**	**28.51**	**30.27**	**32.72**
Budget revenues from taxes and duties related to taxation of oil, gas and petroleum products, which includes:	10.18	9.65	10.01	7.42	6.12	6.84	9.03
MET on oil	3.13	2.99	3.11	3.25	2.72	3.64	5.04
MET on gas	0.39	0.44	0.47	0.51	0.57	0.73	0.75
Export customs duties on oil	3.65	3.19	3.31	1.72	1.20	1.06	1.49
Export customs duties on gas	0.64	0.66	0.62	0.66	0.62	0.63	0.78
Export customs duties on petroleum products	1.66	1.65	1.88	0.90	0.52	0.43	0.62
Customs duty (when crude oil and certain categories of petroleum products were exported from Belarus outside the Customs Union)	0.17	0.14	0.14	0.0	0.0	0.0	0.0

Source: [56].

The issue of rent withdrawal by the owner (state) from oil and gas companies is outside the scope of this study. The authors would like to focus on the issue of rent redistribution.

It should be noted that state ownership prevails in the raw material sectors of most countries exporting natural resources. Almost all countries rather tightly control the sphere of subsoil use. Sovereign funds shall be accumulated due to "excessive" (with regard to the level defined by the national legislation) and/or additional incomes (in case of favorable conditions in the world market) of the budget for the following purposes:

– State budget stabilization (Reserve (stabilization) funds)
– Compensation to the population for resource depletion (Future Generation Funds)
– Supporting the economy in times of crisis (Budgetary Reserve Funds)

However, the principles of establishing sovereign funds, redistribution, and use of rental income are different. For example, Saudi Arabia, the United Arab Emirates, and Algeria accumulate excess income on separate accounts. Norway, Chile, Kuwait, and Oman transfer excess income to specially established nonrenewable resource funds.

As an example of successful oil and gas stabilization funds but different in the use of rental income, we can cite the experience of such Arctic countries as Norway and the U.S., Alaska.

The Norwegian Government Pension Fund Global (GPFG) was established in 1990 and is the largest in the world [57]. GPFG was set up to form reserves in the period of stable or high oil prices, or general economic recovery in view of the worsening demographic situation and reduction of oil revenues in the future due to exhaustion of resources. The state participates in the oil and gas sector as the owner (Statoil, Petoro, and Gassco companies) and as a shareholder of private companies. The fund is formed with the state income from participation in oil and gas projects arising when prices for hydrocarbons exceed the expected level, as well as with the fund's investments. The Central Bank manages the Fund, but the funds are strictly controlled. Neither the government nor the Central Bank may spend funds without a resolution of the Parliament. The funds are used as follows: in the short term—to cover the budget deficit; in the long term—to finance social expenses that are increasing due to the population aging, and to compensate losses to the future generations due to exhaustion of hydrocarbon reserves. The fund's money is invested mainly in foreign assets due to limited opportunities to place it in the country. Norway is the leader of the HDI ranking (Human Development Index) [58], which is indicative of the country's successful socio-economic policy and effective management of the oil and gas sector.

Alaska Permanent Fund (APF) was established in 1976. Constitutional Budget Reserve Fund (CBRF) was established in 1990. Oil is owned by state citizens only. APF was set up to accumulate rental income and create an investment base for future generations. The fund is formed with oil industry payments (25% of the state budget revenues). The governor and the legislative power annually decide how to use the funds; a part of which (42%) is paid to residents of the state. The remaining part is invested. CBRF is meant to finance the state budget deficit. The fund is formed with a share of tax revenues from the oil industry. Funds allocated to the government must be returned later. Despite the harsh natural and climatic conditions, the state population is increasing [59], which indicates the effectiveness of rental income management and the socio-economic policy.

The Stabilization Fund of the Russian Federation was established in 2004. As a result of the reorganizations, the fund now exists as the Russian National Wealth Fund (NWF), which receives rental income for further redistribution. MET, customs duties from hydrocarbons (including those from Russia's continental shelf) are transferred to the federal budget of the Russian Federation at 100% standard, forming NWF with additional oil and gas revenues of the federal budget. The money is used to co-finance voluntary pension savings and to cover the deficit of the Pension Fund and the federal budget.

Transferring 100% of rental income to the federal budget is explained by the fact that, according to the Law of the Russian Federation "On Subsoil", subsoil assets are the state property [6]. Moreover, it has been proven that if the population exceeds 50 million people, the targeted redistribution of rental income will be ineffective [60].

The analysis of the ability to achieve a high income due to hydrocarbons in Russia.

The authors used their methodology to analyze the ability to achieve a high income due to hydrocarbons in Russia:

1. The major countries producing hydrocarbons and establishing oil and gas sovereign wealth funds were selected for the comparative analysis: Russia, Saudi Arabia, Iraq, United Arab Emirates, Iran, Kuwait, Nigeria, Qatar, Norway, and Algeria (Table 5).

Table 5. Major countries producing hydrocarbons and accumulating oil and gas sovereign funds.

Country	Oil Production in Millions of Tonnes in 2019	Natural Gas Production in Billions of m^3 per Year in 2019	Hydrocarbons Were the Source for Funding Sovereign Wealth Funds
USA	747.7	955.1	
Russia	568.1	703.8	Yes
Saudi Arabia	556.6	117	Yes
Canada	274.9	190.5	
Iraq	234.2	11.6	Yes
China	191	170.2	
United Arab Emirates	180.2	55.1	Yes
Iran	160.8	253.8	Yes
Brazil	150.8	23.8	
Kuwait	144	14	Yes
Nigeria	101.4	47.8	Yes
Qatar	78.5	183.6	Yes
Norway	78.4	119	Yes
Australia	64.3	151.9	
Algeria	20.6	89.6	Yes

2. Table 6 shows the results of the *Ira* calculation, data on GNI per capita (PPP) by country.

Table 6. Results of assessing the ability to achieve a high income due to hydrocarbons.

Country	Gross National Income (GNI) Per Capita, PPP, $ *	Territory of a Country in Thousands of km^2	Population Size in Millions of People	*Ira*
Countries with GNI per Capita above the Average Value				
Qatar	110,489	11.59	2.64	59.15
Kuwait	71,164	17.82	4.59	24.58
Norway	68,059	385.21	5.37	5.53
United Arab Emirates	66,912	83.60	10.21	11.03
Saudi Arabia	49,338	2149.69	34.22	3.44
Countries with GNI per Capita below the Average Value				
Russia	25,036	17,125.19	146.75	1.03
Iraq	15,365	435.05	37.06	2.74
Iran	18,166	1648.20	84.20	1.41
Algeria	13,639	2381.74	38.09	0.45
Nigeria	5086	923.77	203.01	0.46
Average GNI per Capita, PPP, $	**40,259**			

* According to (Human Development Index) [58].

The analysis has revealed that the area and population size affect the ability of a country to achieve a high income due to hydrocarbons. Only when the *Ira* exceeds 3, GNI per capita can rise above the average value. Thus, the large territory of Russia and its population size prevent the implementation of a rent-focused government policy to increase income.

In the foreseeable future, it is not possible to create and develop branches of industry, other than mining and related industries, in AZRF for a number of reasons:

1. Specific regional restrictions and risks for companies. It is difficult to imagine that businesses will choose the Arctic to deploy enterprises of light industry, agriculture, chemical industry, high-tech instrumentation, etc. We can find good examples of successful development of agriculture in the Arctic territories both in Russia and in other Northern states (Sweden, Finland, Norway, Iceland, Alaska (the USA)). Due to the climatic peculiarities of the Arctic countries, agriculture is mainly subsidized and is aimed at food self-production. Agriculture development is not considered as a backbone industry in AZRF because the country has Southern regions with more favorable climatic conditions. Launching production facilities in AZRF will lead to higher expenses compared to the average figures in industries. So, companies' activities will be less efficient and their products will be less competitive in AZRF. The main reasons:

    - Production in extreme climatic conditions. Equipment, technologies, and materials are to be adjusted to the Arctic conditions.
    - The Arctic fragile ecosystem must be taken into consideration. Lack of natural light, low temperatures, strong winds, and drifting ice lead to low self-restoring and self-cleaning capacity of the ecosystem.
    - Complicated logistics: material and technical support to remote facilities and remote location from the main centers of the final product consumption.
    - Employee requirements and, as a result, provision of conditions attracting qualified personnel (with the number of employees required for the implementation of the AZRF development programs).

2. The need to preserve the traditional way of life of the indigenous population, which is incompatible with a high level of industrialization. The problem of harmonization of socio-economic interest

system in AZRF, the impact of the industrial development on the traditional way of life of indigenous peoples in the Arctic were considered by the authors in [7].

The existing regional restrictions for launching production facilities not related to the mining industry, lead to increased attention to the rational use of raw materials. Minerals are the main component of AZRF's regional wealth in the long term [61,62]. Minerals are non-renewable resources. They are not developed in the region, but are exported. This fact reduces AZRF's regional wealth and leads to resource depletion [63,64]. Rental income is withdrawn to the federal budget, while regional resources are exhausted. At the same time, the local population bears all the consequences of industrial development of the region (deterioration of the environmental situation, threat to the traditional way of life of Arctic indigenous peoples, transformation of natural landscapes, loss of ecosystems, reduction of biodiversity, etc.). As an example, we can cite an environmental disaster in Norilsk on 29 May 2020: 21,163 tonnes of diesel fuel was spilled into the Daldykan and Ambarnaya rivers and their tributaries from CHPP-3 owned by Norilsk-Taimyr Energy Company (which is a part of PJSC MMC Norilsk Nickel). The Russian Federal Service for Supervision of Natural Resources estimated the environmental damage at nearly RUB 148 bn (about USD 2 bn) [65]. According to Greenpeace Climate and Energy Campaign Coordinator V. Yablokov, it will take more than a decade to eliminate the consequences of the disaster [66]. Moreover, during this period, the local population will bear all the consequences of environmental pollution.

Thus, a colonial development model is observed in the Arctic zone. Implementation of strategic federal and corporate programs have allowed achieving economic growth in AZRF (Table 1). However, the authors believe that implementation of the colonial model will lead to a "growth without development", which contradicts the concept of "sustainable development" [67,68]. Figure 4 shows the changing share of AZRF's GRP in Russia's aggregate gross product and the dynamics of AZRF's resident population through 2014–2018.

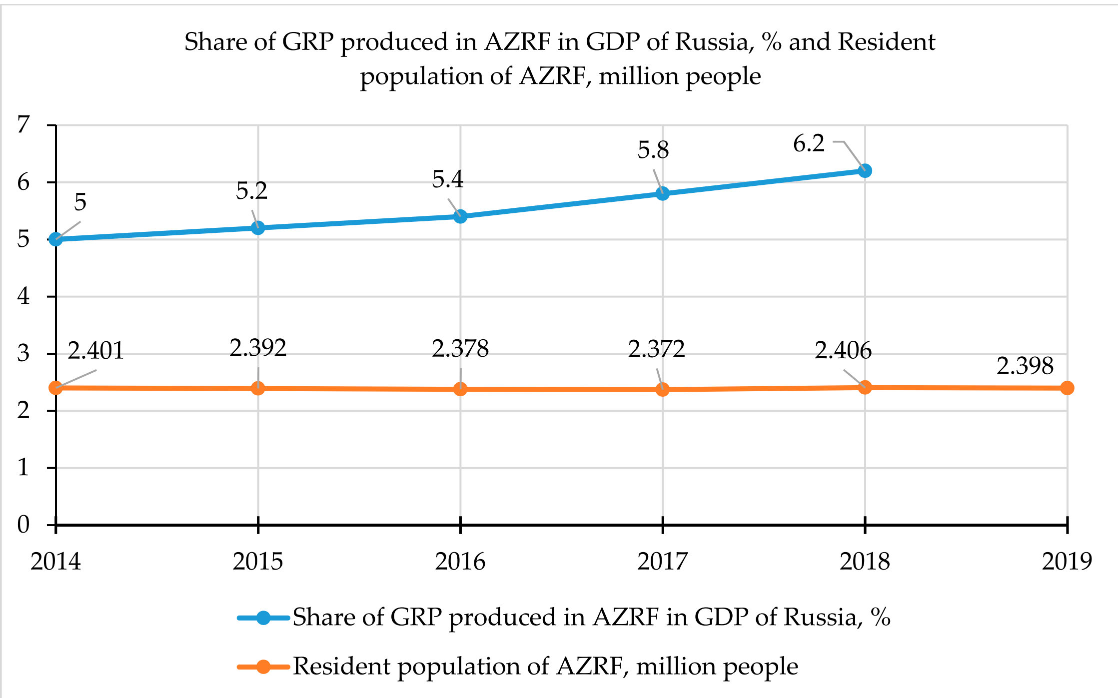

Figure 4. Dynamics of AZRF's GRP share in Russia's GDP and population of AZRF (compiled by the authors considering data [49,53]).

The analysis of the dynamics of AZRF's GRP share in Russia's GDP and population of AZRF (Figure 3) proves the hypothesis: a colonial economic model has been established in AZRF. The gross product growth is not accompanied by improving quality of life, as there is no direct correlation between the changing GRP and the population size. Intensification of the regional industrial development occurs together with a decrease in population, which indicates extensive economic growth. Development of the resource potential of Russia's Arctic territories should not deteriorate the situation in the Arctic region. According to the authors, it is possible to change the quality of economic growth only by increasing the level of the region's socio-economic development. The main indicator of a change in this area will be the dynamics of territory depopulation processes.

In 2015, 193 member states of the United Nations adopted 17 Sustainable Development Goals within Transforming our world: the 2030 Agenda for Sustainable Development [69]. The Sustainable Development Goals are integrated and indivisible and balance the three dimensions of people's lives: the economic, social, and environmental. The authors have proven [7] that AZRF is a high responsibility zone for the state. Among risks directly depending on the state control of the Arctic development, are the following economic, social, environmental, and financial risks:

– Risks connected with social and economic underdevelopment: shortage of manpower; decline in labor efficiency; migration of the population to more favorable regions, etc.
– Risks of technical and scientific lagging behind: lack of technology in mineral resource exploration and production.
– Environmental safety risks: subsoil users spill oil, emit hazardous air pollutants, violate waste disposal standards, and do not contribute to mined-land reclamation.
– Risks of insufficient state funding: absence, or underdevelopment of infrastructure, housing construction, etc.

Maintaining the existing principles of rent income redistribution endangers fulfillment of the Sustainable Development Goals concerning the population, health and prosperity of people, ensuring decent and efficient work, and successful entrepreneurship.

The Ministry for Development of the Russian Far East and Arctic has cut down the financing of the state program for AZRF development till 2025 by RUB 50 bn, from RUB 190 bn to RUB 140 bn [70]. At the same time, in order to increase investment activity, the government plans to introduce tax benefits for the income tax, VAT, MET, property tax, land tax, etc., up to zeroing rates for a number of taxes (including MET) [71]. These measures seem to be reasonable considering a decline of the Russian economy and the world economy in general caused by the COVID-19 pandemic. Nevertheless, the authors doubt that rent tax rates should be zeroed due to their special nature. Preferential rates on income tax, property tax, etc., increase the profit of mining companies. The government can take this measure in order to improve the attractiveness of investment projects and business activity in AZRF. However, the zeroing of rent taxes leads to appropriation of unearned income by a company. Thus, rental income neither remains in AZRF nor is transferred to the federal budget but is redistributed to mining companies.

The issue of exhaustible natural resources requires not only rational use of the income received, but also makes one think about how this income should be redistributed in the society. According to the authors, in order to change the quality of economic growth and to improve living standards in AZRF, it is necessary to leave rental income in the region until its level of socio-economic development reaches at least the average Russian level. For attraction of additional manpower needed to implement the strategic directions of AZRF development, the region's level of social and economic development should be higher than the Russian average one in order to compensate for the harsh natural and climatic conditions of the region and to achieve a growth rate of manpower corresponding to the pace of AZRF's industrial development.

It has been proven that it is possible to achieve an acceptable standard of living at the expense of resource rent with a population of about 5 million people [72]. As of 2019, AZRF's permanent population totaled 2.4 million people (Table 2). So, the redistribution of rental income received by

AZRF from the federal budget in favor of the Arctic regions may create the necessary conditions for improving the region's level of socio-economic development.

AZRF is characterized by extremely low population density. About 1.6% of Russia's population lives in AZRF, which accounts for 20% of the country's total area. Moreover, AZRF is characterized by very uneven settlement (Figure 5).

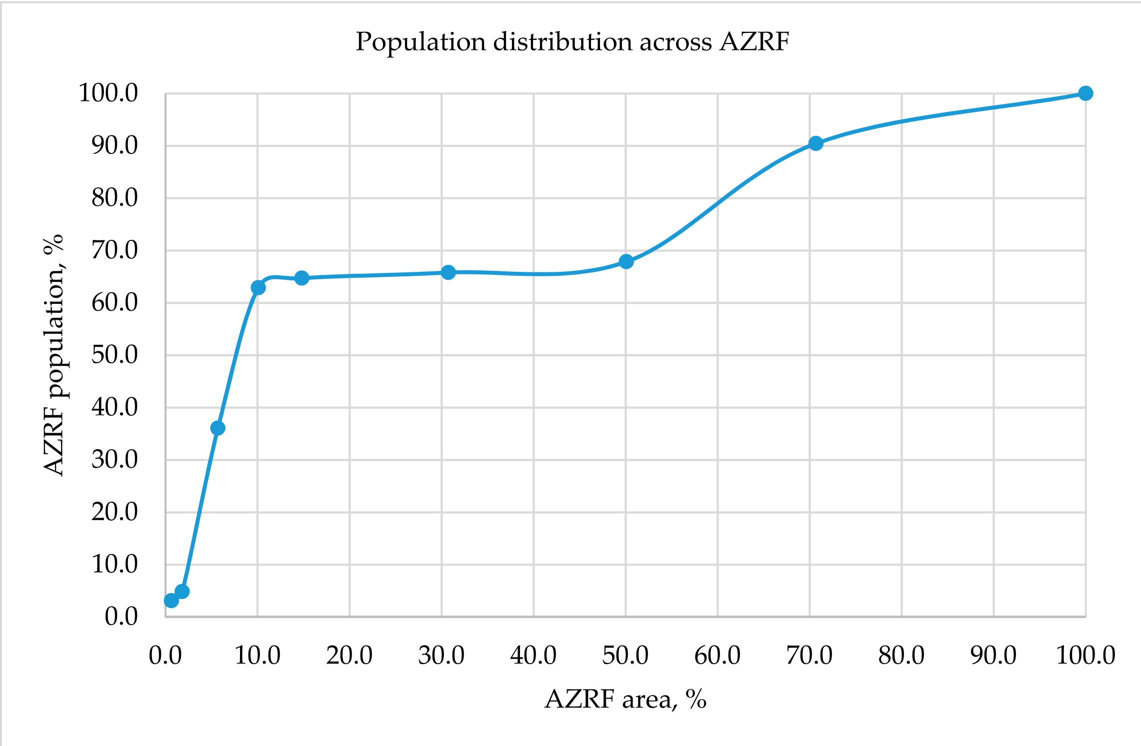

Figure 5. Population distribution across AZRF (calculated by the authors considering data of the Federal State Statistics Service (Rosstat)).

The analysis has revealed that over 60% of the region's population lives in the territory occupying 10% of AZRF's total area. The Arctic Zone's large territory requires consolidation of rental income to increase the region's level of socio-economic development (to develop transport and social infrastructure, power supply, etc). The large territory, low population density, and uneven settlement prevent the region's development with the targeted redistribution of rental income. So, Alaska's successful experience (targeted redistribution of the rental income) seems to be hardly applicable in AZRF conditions.

By the order of the President of Russia Vladimir Putin as of 23 November 2020, [73] the government plans to optimize development institutions in Russia, including the Arctic development institutions: some of them will be closed down, others will be enlarged. The development institution reforming period is the right time to revise the principles of rent income redistribution. Results of the authors' research show that the targeted redistribution of rental income will be ineffective in AZRF. So, it seems expedient to set up the Arctic fund, where rental income from oil and gas field development will be transferred. It will allow the state to accumulate funds for the implementation of infrastructure and social projects, as well as for the region's development. Still, the elaboration of a mechanism for rental income redistribution remains the subject of further research in improving the system of rental relationship in AZRF.

4. Discussion and Conclusions

Rent issues have been developed for decades, remaining in the focus of scientific and applied research. Different aspects of the issue are considered in the works of representatives of classical, neoclassical economic theory and institutional economics. The system of rental relationship (the core of economic relations for countries with the rental economy model) determines the efficiency of withdrawal and redistribution of rental income considering exhaustibility of resources and the ability of countries to conduct a successful socio-economic policy and modernization of the economy. It is still a debatable issue whether the abundance of natural resources is a "Resource Curse" causing the "Dutch disease", or competitive advantage for achieving a high standard of living [71,74–77]. Currently, the world's practice shows that some countries very successfully use their raw material potential providing a high standard of living for their citizens (Norway, UAE, Qatar), while other states are lagging behind in terms of the main indicators of socio-economic development (Venezuela, Nigeria). The efficiency of the system of the rental relationship depends on many factors: the quality of economic policy, institutions, principles of rental income redistribution, population size, and territory of countries.

Russia has chosen consolidation of rental income in the federal budget. It is reasonable due to the large population and territory of the country [5]. However, considering the current world crisis, the ongoing mobilization policy intensifies the issue of "exhaustibility of resources" in AZRF, threatening possible sustainable development of the region.

As a result of the research, we make the following conclusions:

1. AZRF is and will remain the most important geopolitical and geo-economic macro-region of the country. However, the level of socio-economic development of AZRF's territories threatens the country's strategic plans for large-scale development of the Arctic. Possible extraction of the Arctic offshore oil and gas largely determines the level and quality of the region's development.
2. Principles of the state policy in the Arctic and strategic plans of the largest companies operating in the region consolidate the raw material nature of AZRF development, making rent the main form of income.
3. The existing regional restrictions for launching production facilities not related to the mining industry, lead to increased attention to the rational use of raw materials. A colonial development model is observed in the Arctic zone: minerals are not developed in the region, but are exported. This fact reduces AZRF's regional wealth and leads to resource depletion. At the same time, rental income is withdrawn to the federal budget, while the local population bears all the consequences of the industrial development of the territories.
4. An improving level of AZRF's socio-economic development and a reduction of territory depopulation will indicate the changing quality of economic growth and the transition from the colonial model of AZRF development to the sustainable development model.
5. It seems reasonable to leave rental income in the region until the level of AZRF's socio-economic development reaches at least the Russian average one. Development of the resource potential should not deteriorate the situation in the Arctic region.

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The Future of Russian Arctic Oil and Gas Projects: Problems of Assessing the Prospects

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Abstract: The development of Arctic marine resources is currently the focus of the world's largest oil and gas companies, which is due to the presence of significant hydrocarbon reserves. However, the decision-making process for implementing offshore oil and gas projects in the Arctic is highly uncertain and requires consideration of many factors. This study presents a comprehensive approach to evaluating the prospects of oil production on the Russian Arctic shelf. It is based on a specific methodology which involves expert forecasting methods. We analyze the current conditions and key factors and indicators, focusing on oil prices and quality of technologies that could influence the decision-making in the oil and gas company concerning Arctic offshore fields' development. We use general scientific methods—analysis, synthesis, classification and systematization—and propose a method for assessing the prospects of Arctic projects which is based on a three-step algorithm. Together with practical tools presented in the article, it will support decision-making on the project initiation and the development of a particular field.

Keywords: Russian Arctic; marine resources; forecasting; expert methods; oil and gas; offshore projects; shelf; prospects

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1. Introduction

At present, the global oil and gas industry is undergoing post-crisis processes and transformation of the energy sector. In March 2020, the price of Brent crude oil reached a record minimum value, below $20 per barrel [1]—the average price of Brent crude oil was about $42 per barrel in 2020 (Figure 1).

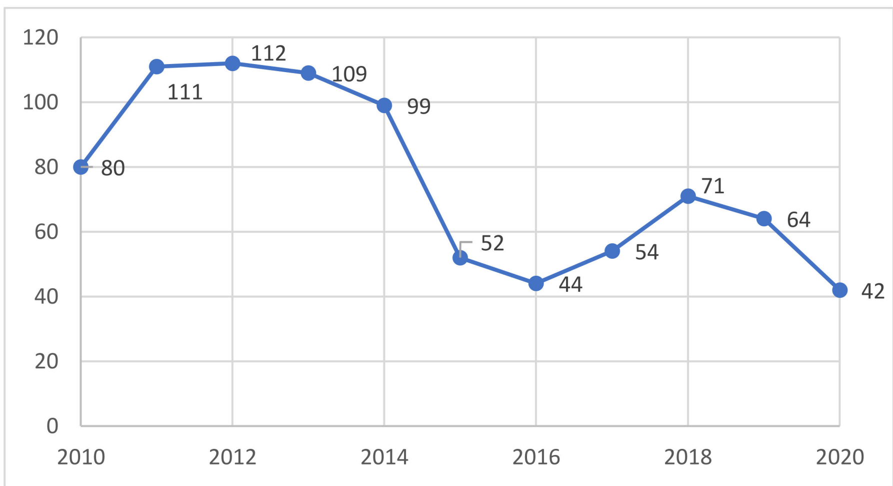

Figure 1. Dynamics of Brent crude oil prices during 2010–2020, USD/bbl. Source: developed by the authors based on [2,3].

Currently, reorganization of the industry is taking place due to the fact that oil could start losing its leading position in the structure of world energy consumption [4–8] as alternative energy sources are developing rapidly [9–13], and the industry is experiencing a number of significant changes, in particular in connection with the COVID-19 pandemic [14–17]. Yet, oil accounted for 33% of the global energy balance in 2019 [3]. However, according to analysts, the share of oil will steadily decline—BP estimates a decrease to 24% by 2030 and 17% by 2040 [18].

Such trends are unprecedented in the global economy and significantly increase the uncertainty throughout the industry, which itself is highly volatile [16]. It makes oil and gas projects with high production costs unprofitable [19]. This is especially true for Arctic marine projects, which are innovative and capital-intensive in nature.

It is well-known that the Arctic has rich hydrocarbon fields in the shelf zone, which is of particular interest to Russian and foreign companies [20–25]. In this regard, it is still debated whether the development of Arctic marine resources is reasonable.

For Russia, oil and gas production in the Arctic has been an important issue for a long time, since it is a powerful driver for the development of the Northern territories and the country's economy as a whole [26,27]. The presence of Russian oil and gas companies in the Arctic is of geopolitical significance [28–31]. In this situation, the problems of developing Arctic mineral resources (including oil and gas) are widely discussed both at the state level and in the academic literature [32–35].

Thus, since 2008, the foundations of strategic management of the Arctic region have been developing in Russia. They are aimed firstly at socio-economic spatial development of territories and ensuring national security. In recent years, a set of basic strategic documents has been adopted which reflect general issues of strategic management and planning, protecting Russia's national interests in the Arctic [36–38], as well as specific problems, such as the development of logistics routes and infrastructure (for example, the Complex plan for modernization and expansion of the main infrastructure of the Russian Federation until 2024, the Development Plan for the Northern Route for the period until 2035, etc.) [39,40], the development of mineral resources, etc.

Some legislative documents (for instance, the strategy for the development of the Arctic zone of the Russian Federation and ensuring national security for the period up to 2020) were valid until 2020. In March 2020, the Fundamentals of the State Policy of the Russian Federation in the Arctic for the period up to 2035 were adopted [36]. One of the purposes of this document is to propel the economic development of the Russian Arctic zone and increase their contribution to the country's economic growth. In November 2020, the strategy for the development of the Russian Arctic zone and ensuring national security for the period up to 2035 was adopted [37]. It presents the main objectives, as well as the tools for the development of the Russian Arctic.

An approach aimed at forming "reference zones" (points of growth) in the Arctic seems interesting. It is established as the main tool for implementing state policy in the Arctic and assumes the development of the Arctic territories as an integrated project. Many of the designated "reference zones" (Kola, Nenets, Taimyro-Turukhansk and others) are focused on raw materials, which confirms the critical importance of implementing oil and gas and other mineral resource projects in the Arctic.

As for academic literature, many researchers devote their works to certain aspects of Arctic territorial development: issues of economic development [26,41], attracting labor resources to the Arctic [42,43], national and environmental safety [30,44], development of hydrocarbon fields in the Arctic seas [45], territorial peculiarities in the Arctic [46], assessment of associated risks [32,47] and many others.

In this regard, due to the complexity and uncertainty about the future of Arctic projects, works in the field of strategic planning and forecasting are of interest. Some of them represent practical tools, such as scenario-based roadmap method and scenario planning [48,49], the choice of a policy implementation strategy based on the forecast of its effectiveness [50], retrospective forecasting and strategic planning maps [51].

For example, Kondratenko makes an attempt to form an effective program for the development of the Arctic shelf based on economic and mathematical modeling [52]. This approach considers the various aspects of the objects analyzed and justifies investments in Arctic offshore oil and gas projects using its own methodology of multi-criteria analysis.

The opinions of researchers and experts regarding the prospects for the development of oil and gas marine resources in the Arctic are radically different. Many experts oppose the development of such deposits due to the commercial inefficiency of projects and the need to import foreign mining technologies. Others, on the contrary, are in favor of implementing projects in the Northern seas due to their positive effects on the Arctic regions, such as improvement of the demographic situation and standard of living. Experts also argue that this opinion is based on the need to strengthen Russia's geopolitical position in the Arctic and improve the image of the Russian oil and gas industry, to prepare for the development of the Russian Arctic shelf [28–30,44,53].

The complexity of Arctic hydrocarbon production projects is due to the influence of a wide range of factors that should be considered when making decisions concerning their future. At the same time, many indicators are qualitative, and the process of evaluating the prospects is difficult to formalize. All this significantly increases the uncertainty surrounding the project and affecting the decisions on its implementation.

It is obvious that oil prices determine the efficiency of hydrocarbons production in the Arctic seas [27,54]. The quality of technologies for offshore production also plays a significant role. In fact, these are the key factors which determine the expediency of developing Arctic offshore hydrocarbon resources, and from this viewpoint, it is inappropriate to talk about high commercial effectiveness of such projects at the moment. However, oil prices' growth, the emergence of new technologies for offshore production and other factors will raise this issue again.

As a result of a thorough analysis of the literature, we have come to the conclusion that there are few studies in the field of evaluating the prospects for the implementation of Arctic offshore projects. In particular, Morgunova presents methods of scenario planning for the development of Arctic shelf deposits in the long term [33]. However, the described scenarios provide only general guidelines concerning the future development of Arctic marine resources and do not consider the prospects for specific oil and gas projects. This confirms the relevance of our research, which is a systematic approach to the problem.

In this work, we use the phrase "forecasting the prospects of an oil and gas Arctic offshore project," meaning that evaluating the long-term prospects of such projects should be based on expert forecasting methods. The prospects of an Arctic oil and gas offshore project appear as its qualitative characteristic, which determines the possibility of their commercially effective implementation. The obtained forecasts will demonstrate the economic performance of the specific offshore project in the long-term.

Our earlier analysis of the possibilities of applying traditional forecasting methods (expert and statistical) to assess the prospects for developing Arctic marine hydrocarbon fields showed that expert methods (expert surveys) are indispensable for such an assessment. Statistical forecasting methods are not applicable for long-term forecasting purposes due to high uncertainty and variability of the external environment and lack of necessary statistical information on the studied indicators [55–57]. In this regard, we hypothesize that the use of expert surveys is the only possible way to form adequate long-term forecasts in this research field.

Thus, the research problem is that the decision-making process for the development of the Arctic offshore field is complex and requires an appropriate scientific base. For that, we propose a systems approach to the problem that will help managers of oil and gas companies make qualified decisions.

Taking into account the above, the purpose of this work is to develop a universal conceptual and methodological approach to forecasting the prospects for offshore hydrocarbon production projects in the Arctic. The practical value of the study lies in the developed system of specific indicators, toolkits and method for forecasting the prospects of an oil and gas Arctic project. From the analysis, we conclude that (i) long-term forecasts of the prospects of Arctic marine oil and gas projects should be based on up-to-date expert opinions, and (ii) decisions on the project implementation should be supported by scientific research and involve specifically designed practical tools. For that, we recommend using the methodology described below.

2. Materials and Methods

During the research, we used several scientific methods, such as scientific analysis and synthesis, classification, systematization and decomposition. We applied commonly used short-term and long-term forecasting methods—extrapolation and expert methods mainly, as well as consensus forecasts.

In the beginning, we paid special attention to such critical aspects as post-pandemic oil prices' forecasts, the development of offshore oil production technologies and the break-even point of Arctic oil and gas projects in the Arctic. Yet, we hypothesize that decision-making on Arctic offshore projects' implementation should consider a wider range of factors and specific indicators.

Then, we systemized all factors and indicators that may hold back or, on the contrary, facilitate the implementation of the project. It allowed us to highlight six key factors which influence the project's prospects. We call them TESCIMP factors, which stand for Technologies (T), Environmental Safety (ES), Climatic and geological factors (C), Infrastructure (I), Macroeconomic factors (M) and Political factors (P). A more detailed description of each factor and its influence on project prospects was provided in our previous research [58]. Indicators inherent to each specific project were classified in four groups in accordance with two criteria—"controllability" and "necessity"—forming a matrix of TESCIMP indicators. The controllability criterion allocates indicators into two groups—"manageable" and "conditionally manageable" ones. It reflects the ability of managers to control and influence the values of TESCIMP indicators. The necessity criterion divides indicators into two groups—"essential" and "stimulating"—depending on the significance of each indicator and the contribution it makes to the assessment of the project's prospects. The essential indicators are qualitative and are used to assess the project's prospects in current conditions based on the conformity of their real values to the desired ones, with the help of a special checklist. Stimulating indicators are quantitative and help evaluate the project's prospects according to the method described below. The full list of indicators can be found in our previous research [58].

Finally, we assume that forecasting the prospects of the Arctic offshore projects should be carried out in the framework of our previously developed TESCIMP methodology. In addition to the classification described above, it involves special practical tools which facilitate solving the problem. They are included in the research algorithm presented below. All these form a complex system and present a comprehensive approach to forecasting the prospects of an Arctic offshore project.

3. Results

3.1. Oil Prices and Technology Development as Crucial Points of Arctic Oil and Gas Projects' Prospects

As noted above, the main factors determining the future of oil and gas projects on the Arctic shelf are oil prices and technology. Oil prices, especially in the face of energy transition, are difficult to predict, and even general trends (positive or negative) for oil prices are hard to forecast. Regarding the new technologies for oil production in the Arctic, the level of their development varies in different countries. As for Russia, predicting the level of technology development is an extremely difficult task. The important thing is that they can have a significant impact on reducing the level of operating costs (OPEX).

Figure 2 provides the analysis of post-pandemic oil price forecasts by the U.S. Energy Information Administration (EIA) and energy companies such as Shell, Eni and BP. In addition, it shows the consensus forecast of oil prices until 2030.

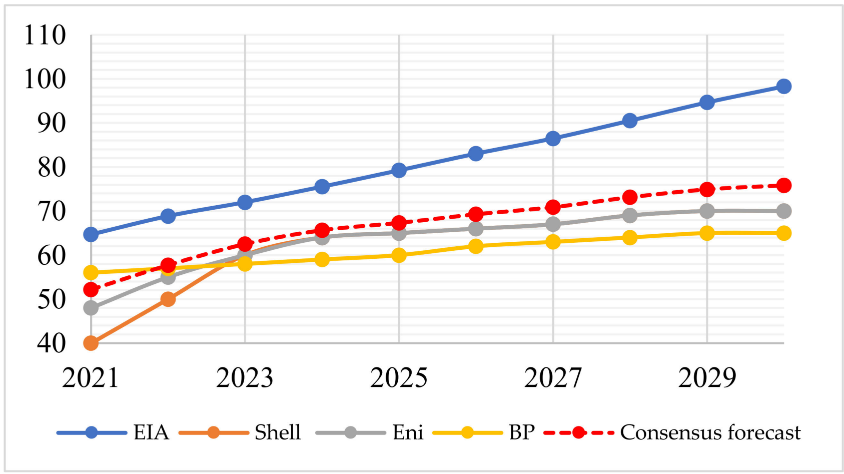

Figure 2. Long-term Brent crude oil price forecast until 2030, USD/bbl. Source: developed by the authors based on [1,59].

According to the forecasts presented in Figure 2, oil prices will grow. We can conclude that under the optimistic scenario (close to the EIA estimates), oil prices will gradually increase to $100 per barrel by 2030. In the pessimistic scenario (close to BP's estimates), oil prices will vary in the range of $60–$65 per barrel.

As for the level of operating costs in oil production on the Russian Arctic shelf, experts' estimates differ significantly. According to the latest estimates of the Ministry of Energy of the Russian Federation, the break-even point of oil marine projects in the Arctic is about $50–$70 per barrel [60]. Some experts assess the costs at the level of $42–$43 per barrel [61]. However, this is an average estimate for all fields in the Arctic, and it will differ for each specific project. Thus, according to Gazpromneft company, the cost of oil production at the Prirazlomnoye field (the only fully launched oil project on the Arctic shelf) will be less than $10 per barrel after all investments are made and the project reaches its full capacity [62].

The Norwegian company Equinor states that the break-even point of Johan Castberg oil field is less than $35 per barrel, and Equinor's portfolio reached a break-even point of $27 [63,64]. Norway has made great strides in the development of Arctic hydrocarbons, demonstrating record low OPEX for offshore oil production. In general, the breakthrough technologies' development can open up new opportunities for oil production in marine fields, including Russian oil and gas companies.

It should be noted that in addition to OPEX, the amount of capital expenditures (CAPEX) is also critically important. According to experts, the cost of drilling on the shelf is 10 times higher than on land, and on the Arctic shelf it is about 27 times higher [65]. The development of drilling technologies may also be a powerful driver to enhance the development of Arctic oil and gas projects.

At the same time, each Arctic project is unique (which is also confirmed by different estimates of the cost of oil production on the Arctic shelf), has a different geographical location and, accordingly, different infrastructure and geological conditions, and determining the prospects for such projects cannot be based only on oil prices and technology development. It confirms the need for a thorough analysis of each particular case and project with the involvement of experienced experts.

3.2. Method for Assessing the Prospects of an Oil and Gas Project on the Arctic Shelf

After the analysis, we came to a conclusion that expert forecasting methods are a significant tool that could help managers prepare justified long-term forecasts for the prospects of an oil and gas project on the Arctic shelf.

As the result of this study, we present a method for assessing the prospects of projects on the Arctic shelf. It can be used by managers of oil and gas companies having specific plans for extraction of hydrocarbons from the Arctic shelf zone as an additional instrument for assessing the prospects of such projects. It is a formalized method for considering expert opinions in the decision-making process.

This toolkit is based on an algorithm that helps to apply a complex approach to forecasting the project's prospects and consists of three main stages (Figure 3). The "inputs" of each stage are presented in ellipses on the left side. These are the specific practical tools used within the stage, as well as incoming information. The central part of the algorithm reflects the processes being implemented, and the right part—the results obtained.

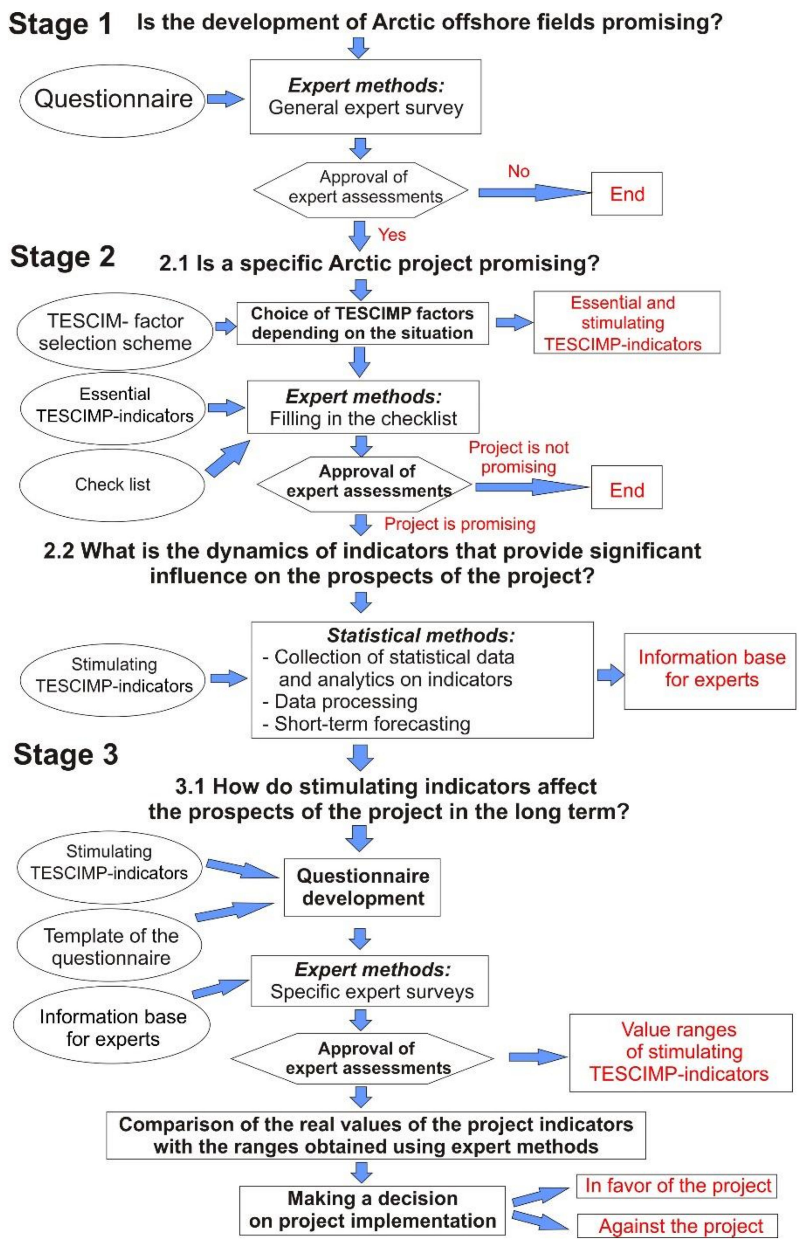

Figure 3. Algorithm of a complex approach to forecasting the prospects of an oil and gas project on the Arctic shelf. Source: developed by the authors.

The first stage of this research is focused on expert forecasting methods in terms of overall prospects for hydrocarbons' production in the Arctic seas. The goal of this stage is to give an answer to the question whether the development of the Arctic shelf is expedient or not. At this stage, specialists of various profiles, scientists and managers of oil and gas companies are involved to ensure the objectivity of the study. The questionnaire of the general expert survey includes the following issues: (i) development of the oil and gas industry as a whole, (ii) prospects and investment attractiveness of offshore oil and gas projects in the Arctic, (iii) state regulation in the field of Arctic marine resources' production, (iv) international cooperation and (v) technological problems of hydrocarbon production on the Arctic shelf. A fragment of a general expert survey questionnaire is presented in Appendix A (Table A1). After the survey, the expert opinions are analyzed and adjusted. The results of this survey provide a comprehensive expert opinion on the prospects for the development of the Arctic oil and gas shelf. It will give a company's manager a profound outlook of key tendencies and problems that will accompany the project to be developed, which will help him make a reasonable decision on initiating a project in the current conditions.

The second stage consists of selecting TESCIMP factors and their corresponding indicators that affect the implementation of a specific project, depending on the situation. Moreover, the output of this stage is an information base for experts which will help to support the decision-making process at the third stage—during the specific expert surveys. This step is based on the TESCIMP methodology and includes the collection and processing of statistical and analytical data for key indicators, and the use of statistical and expert forecasting methods.

In order to determine TESCIMP indicators for assessing the prospects of an oil and gas project on the Arctic shelf, we developed a scheme for selecting TESCIMP factors, which is used every time a decision is made to develop a particular field in the corresponding circumstances (Figure 4). The prospects of the project are estimated by oil and gas companies planning to develop the field.

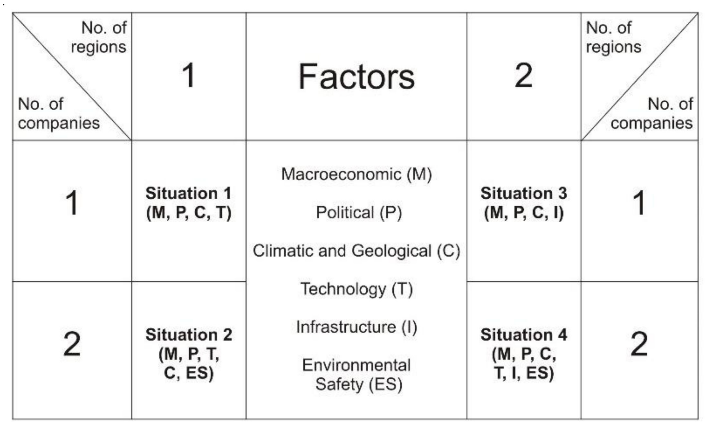

Figure 4. Scheme for selecting TESCIMP factors for evaluating the prospects of an oil and gas project on the Arctic shelf. Source: developed by the authors.

The selected TESCIMP factors and indicators can take different values depending on the field, the operator company and the production region. If the deposits are located in different countries and it is necessary to choose one of the projects, political and macroeconomic factors will play an important role in assessing their prospects. In addition, even for Russian projects, the influence of these factors is crucial, as they create, or do not create, the opportunities for their successful implementation.

Therefore, these factors should be considered when evaluating the prospects of any project. If the fields for the development are located in the same region, technologies and climatic and geological factors will be paramount when choosing one of the alternative projects by one company. This case corresponds to Situation 1 in the scheme. The environmental safety appears to be a crucial factor when there are two or more oil and gas companies applying for the fields' development, since it is directly related to their environmental policy. If there are deposits located in different regions, the values of infrastructure indicators become important for the project precedence.

To assess the prospects of a specific project on the Arctic shelf, we propose to use a checklist which can be formed after selecting TESCIMP factors and the corresponding qualitative indicators (the so-called "essential" indicators). If the real values of each required indicator in the checklist coincide with the desired ones, the project under consideration can be assessed as promising [58].

The information base for experts includes short-term forecasts about the values of particular quantitative TESCIMP indicators (we call them "stimulating" indicators as their values can motivate or demotivate the company for the field development [58]). For this, extrapolation methods using retrospective data are mainly used. In addition, we propose to systematize up-to-date analytical information about the dynamics and current values of the indicators under consideration. An example of an information base for conducting a specific expert survey is presented in our previous research [66].

The third stage is dedicated to specific expert surveys on the prospects of an oil and gas project and uses the outputs of the first and second stages. Its goal is to evaluate how stimulating indicators affect the project prospects in the long term. For specific expert surveys, a template is used as a basis for the special questionnaire, which is updated each time before the research. This is necessary because the questionnaire itself is not static, since it includes stimulating indicators that change depending on the situation of choice of a specific project. As a result of the survey, each stimulating indicator should obtain a range of its values (A, B or C), which is preceded by the expert approval procedure. The ranges of the values of each indicator obtained by the expert method can be written as follows:

$$\text{aij min} \leq \text{aij low} \leq \text{aij high} \leq \text{aij max}, \tag{1}$$

where $a_{ij\ min}$ is the minimum value of the indicator, and $a_{ij\ low}$ and $a_{ij\ high}$ are the values of stimulating indicator a_{ij} limiting the mid-range (B).

If the minimum and maximum value of any indicator is difficult to establish, one can take $a_{ij\ min} = 0$; $a_{ij\ max} \to \infty$.

Figure 5 illustrates how stimulating TESCIMP indicators can be used for constructing a profile of a particular field from the managerial point of view.

An example profile shown in Figure 5 reflects the results of the specific expert survey and serves as an output of Stage 3 of the algorithm. TESCIMP factors used to construct the table are selected according to the scheme (Figure 4). In this case, we present an example of Situation 4 when all six factors are considered. The boundaries of each value interval (i.e., $a_{ij\ min}$, $a_{ij\ low}$, $a_{ij\ high}$, $a_{ij\ max}$) are assessed using expert methods and are the outputs of the specific expert survey. The black curved line is drawn based on the values of a range of indicators (left column) that fall in the corresponding intervals—the so-called "profile" of a project. In this example, the curved line shows a profile of a promising Arctic oil and gas offshore project, assuming that the optimistic oil price scenario will take place. Promising Arctic oil and gas offshore project is defined by the authors in our previous research [58].

Thus, this toolkit is designed to visualize how the real project's quantitative indicators behave relating to the possible value ranges for each indicator. It helps the company's managers compare the real values of the project indicators with ranges A, B and C and prepare an informed decision on the project's implementation.

Moreover, we propose to quantify the prospects of an Arctic offshore oil and gas project.

Suppose m is the number of factors selected according to the above scheme, k_i is the number of indicators for each factor, $i = \overline{1,\ m}$, and a_{ij} is the real values of the project indicators for each factor, $i = \overline{1,\ m}$ and $j = \overline{1,\ k_i}$.

To get the final project assessment, we propose to use a matrix of coincidences of the real values of project indicators with ranges A, B and C. The elements c_{ij} of this matrix are obtained as follows: $c_{ij} = 1$, if the real value of the indicator falls within the range A, i.e., $a_{ij} \in [a_{ij\ min}, a_{ij\ low})$, $c_{ij} = 2$, if $a_{ij} \in [a_{ij\ low}, a_{ij\ high})$, and $c_{ij} = 3$, if $a_{ij} \in [a_{ij\ high}, a_{ij\ max})$.

	Stimulating TESCIMP-indicators	Values of indicators		
		$[a_{ij\,min} \ldots a_{ij\,low}]$	$(a_{ij\,low} \ldots a_{ij\,high}]$	$(a_{ij\,high} \ldots a_{ij\,max}]$
Direct dependency of indicators' values on the project prospects (↑)				
Macroeconomic factors	level of world prices for oil and gas, USD / bbl	0 …40	40 … 70	70 and more
	increase in proved reserves of the Arctic shelf around the project field due to geological exploration, million tons of fuel	*Filled by experts*	*Filled by experts*	*Filled by experts*
	GDP growth rate of the country, %	*Filled by experts*	*Filled by experts*	*Filled by experts*
	savings associated with tax credits for developing Arctic shelf fields, million rubles	*Filled by experts*	*Filled by experts*	*Filled by experts*
Technologies	company's R&D expenses aimed at developing production technologies on the Arctic shelf per unit of output, million rubles / unit of products	*Filled by experts*	*Filled by experts*	*Filled by experts*
	number of innovations implemented in the total number of innovations developed in the oil and gas company, %	*Filled by experts*	*Filled by experts*	*Filled by experts*
	share of intangible assets (rights on IPOs) in the oil and gas company's assets,%	*Filled by experts*	*Filled by experts*	*Filled by experts*
	the share of company's R&D expenses in income (profit), %	*Filled by experts*	*Filled by experts*	*Filled by experts*
	number of patents received, pcs per year	*Filled by experts*	*Filled by experts*	*Filled by experts*
Infrastructure	number of shipyards, machinery plants, factories of building materials and other industrial organizations in the region, pcs.	*Filled by experts*	*Filled by experts*	*Filled by experts*
	density of population in the region, thousand people	*Filled by experts*	*Filled by experts*	*Filled by experts*
	level of deterioration of existing objects of transport and engineering infrastructure in the region, million rubles	*Filled by experts*	*Filled by experts*	*Filled by experts*
ES	company's expenditures associated with environmental protection, million rubles	*Filled by experts*	*Filled by experts*	*Filled by experts*
	PROSPECTS	**LOW**	**MEDIUM**	**HIGH**
Inverse dependency of indicators' values on the project prospects (↓)				
Political factors	oil and gas company's costs in connection with the imposition of sanctions against the Russian oil and gas sector, million rubles	*Filled by experts*	*Filled by experts*	*Filled by experts*
	share of foreign technologies in the total number of applied technological solutions, %	*Filled by experts*	*Filled by experts*	*Filled by experts*
	the share of services rendered by foreign oilfield service companies in the total volume of services rendered, %	*Filled by experts*	*Filled by experts*	*Filled by experts*
Climatic and geological factors	distance from the field to the coastline, km	*Filled by experts*	*Filled by experts*	*Filled by experts*
	depth of the sea on the extraction site, m	*Filled by experts*	*Filled by experts*	*Filled by experts*
	depth of oil / gas occurrence, m	*Filled by experts*	*Filled by experts*	*Filled by experts*
	average percentage of water surface covered by ice on the industrial vessel's way, %	*Filled by experts*	*Filled by experts*	*Filled by experts*
	average wind speed at the mining site, m / s	*Filled by experts*	*Filled by experts*	*Filled by experts*
	average score of sea disturbances on the Beaufort scale, point	*Filled by experts*	*Filled by experts*	*Filled by experts*
	average duration of the period of poor visibility (up to 1 km), days per year	*Filled by experts*	*Filled by experts*	*Filled by experts*
	number of days in a year with ice cover at the place of extraction, days	*Filled by experts*	*Filled by experts*	*Filled by experts*
	duration of the cold season, days per year	*Filled by experts*	*Filled by experts*	*Filled by experts*
Infrastr ucture	distance from the field to the main infrastructure objects (pipelines, tank farms, settlements, roads, railway, sea ports, shipyards, machinery plants, factories of building materials), km	*Filled by experts*	*Filled by experts*	*Filled by experts*
ES	payments for negative impact on the environment, million rubles	*Filled by experts*	*Filled by experts*	*Filled by experts*
	costs in connection with the tightening of industrial and environmental safety requirements, million rubles	*Filled by experts*	*Filled by experts*	*Filled by experts*
	PROSPECTS	**HIGH**	**MEDIUM**	**LOW**

Figure 5. Example profile of a promising Arctic oil and gas offshore project. Source: developed by the authors.

Then, the assessment of the prospects of an Arctic offshore project (PAOP) can be calculated using the arithmetic mean of the elements c_{ij} of the matrix of coincidences:

$$\mathrm{PAOP} = \frac{\sum_{i=1}^{m} \sum_{j=1}^{k_i} c_{ij}}{\sum_{i=1}^{m} k_i}. \quad (2)$$

We propose to interpret the values of the PAOP indicator as follows:

- If PAOP $\geq$ 2.5, the actual project indicators are in favor of the project implementation, indicating its long-term prospects and resistance to external changes.
- If PAOP < 1.5, the project can possibly become unpromising in the long term, projects with such values of PAOP are not recommended for development from the viewpoint of their commercial implementation.
- If PAOP $\in$ [1.5, 2.5), the project is promising under current conditions and has a medium level of stability to changes in the external environment in the long term.

4. Discussion and Conclusions

The purpose of this work was to develop the method for evaluating the prospects of hydrocarbon projects on the shelf of the Russian Arctic. It provided a comprehensive study of the problematic field, analyzed the current situation and developed methodological frameworks and tools for forecasting the prospects of Arctic projects. Consistent application of the proposed methods in accordance with the proposed algorithm will provide answers to key questions:

- Is the development of hydrocarbon deposits on the shelf of the Russian Arctic promising in the current situation and in the medium and long term?
- What factors have a key impact on the prospects of a specific Russian Arctic project and what is the dynamics of the main indicators?

As mentioned above, the problem of forecasting the prospects for the implementation of oil and gas offshore projects in the Arctic is difficult to formalize, which focused this study on expert forecasting methods. The reliability of the results obtained when conducting general and specific surveys was achieved by attracting a large number of experts and the approval procedure, which is reflected in the research algorithm.

This work offers an approach to forecasting the prospects for offshore projects based on a comprehensive study of its pros and cons, consideration of a large number of factors and indicators that influence them. We assume this will allow an unbiased approach to the problem of choosing the most promising project for implementation and will serve as the basis for an effective decision-making process.

The proposed method provides recommendations to managers of oil and gas companies regarding the implementation of offshore Arctic projects. Due to the high uncertainty surrounding the decision-making on the development of deposits, as well as the multidirectional influence of numerous factors, especially qualitative ones, a more precise assessment seems difficult, and its need is debatable.

In general, the results of the study are focused on the long-term perspective, since they lie in the field of strategic planning and forecasting of such long-term and expensive projects as the development of marine oil and gas fields in the Arctic. They can be used by government agencies and oil and gas companies engaged in the development of the Russian Arctic shelf when initiating and planning such projects.

Further research will be devoted to validation of the proposed method with other cases and forecasting the prospects of particular oil and gas projects on the Russian Arctic shelf. The study will be conducted for the management situation, which involves choosing one of several potential projects and is characterized by its own set of key factors. The proposed approach is designed to support decision-making for managers of oil and gas companies and helps them in dealing with a complex structure and difficult to forecast practical and scientific problem.

The research led to the following conclusions:

1. Despite the fact that the key determinants of interest in the Arctic shelf are oil prices and available Arctic drilling and oil production technologies, the development of marine resources of the Russian Arctic is dependent on a large number of various indicators, each of them having a different impact on the project's prospects. The role of innovations is increasing significantly [34], as well as the parameters of sustainability of oil and gas projects in the Arctic [67]. At the time of the research, the expediency of such projects could be characterized as doubtful.

2. The ongoing crisis associated with the COVID-19 pandemic hit the industry hard, and, particularly, the offshore Arctic projects. Being doubtful before the pandemic, in the current global conditions, they lose any potential profitability.
3. Despite the current commercial inefficiency of the Arctic projects, Russia continues supporting Arctic offshore projects. This is due to the fact that the implementation of hydrocarbon projects in the Arctic is strategically significant for the Russian Federation. It can also be confirmed by recently adopted strategic plans of the government on the development of Russian Arctic and marine resources [36,37]. Obviously, such projects in the current macroeconomic situation will require more government support.
4. The state support of Arctic projects becomes a crucial essential indicator for its initiation in the current conditions. This should be kept in mind as an important assumption when forecasting the projects' prospects until the macroeconomic situation changes significantly.

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Appendix A

Table A1. Fragment of a general expert survey questionnaire—Objectives of the state and business in the implementation of offshore projects.

Question	Possible Answers	Your Answer
What, in your opinion, should be the state regulation of the development of the shelf and the implementation of offshore projects? (check one box only)	Direct participation of the state–direct contribution and participation of the state in the economic, financial, scientific and industrial spheres	
	Indirect participation of the state–formulation at the state level of rules, norms, strategies that determine the development vector and targets	
	Combination of direct and indirect state participation	
	Other: ______________________	
Do you consider the current state regulation in the field of shelf development to be effective? (check one box only)	Yes, current government regulation can be considered effective	
	Yes, the current state regulation can be considered effective, but requires improvements	
	In general, the current state regulation can be considered quite effective, but there are problems with the declarative nature of the main policy documents and initiatives	
	In general, current government regulation can be considered quite effective, but there are problems in the area of interconnection of the main policy documents and initiatives	
	No, the current government regulation cannot be considered effective, significant adjustments are required	
	Other: ______________________	

Table A1. *Cont.*

Question	Possible Answers	Your Answer
What aspects of state regulation of shelf development require improvement? (check one or more boxes)	Legal regulation in general, the legal framework for the development of the shelf	
	Tax policy	
	Licensing issues, procedure for granting the right to use subsurface areas	
	Financial mechanisms, development of financial instruments	
	Information security	
	Development of environmental standards	
	Implementation of state control	
	Other: ___________________________________	
What can be considered the main goal of the government in the implementation of Arctic shelf projects? (check one or more boxes)	Ensuring effective international cooperation	
	Increasing geological knowledge	
	Stimulating R&D in this area	
	Building strategies for the commercialization of R&D results in this area, taking into account the interests of all stakeholders	
	Ensuring sustainable development of industries producing up-to-date machinery in this area (oil and gas engineering and related industries)	
	Development of small and medium-sized businesses (oilfield services)	
	Ensuring sustainable social and economic development of the Arctic region	
	Other: ___________________________________	
Is it necessary to liberalize the admission of private companies to work on the Russian shelf? (in order to attract additional funding, innovations, etc.) (check one box only)	Yes, it is necessary	
	Yes, it is necessary to perform individual tasks	
	No, there is no need	
What can be considered the key problems for business (oil producing companies) in the implementation of offshore projects? (check one or more boxes)	High bureaucracy at all stages	
	Imperfect tax regime	
	High capital intensity of projects	
	Funding problems	
	High prices for raw materials, resources, services (high production costs)	
	Inadequate provision with domestic equipment and technologies	
	The need for implementation of related infrastructure projects	
	The tightening of environmental legislation	
	Lack of qualified personnel	
	Other: ___________________________________	
What can be considered the main goal of business in the development of the Arctic shelf?	The preservation/development of cooperation with foreign partners	
	Proactive participation in solving issues related to technological security of projects	
	Proactive participation in solving issues related to ecological safety of projects	
	Interaction with scientific and educational organizations	
	Other: ___________________________________	
What can be considered the key business objectives in improving the technological security of offshore projects?	Creation and development of private R&D centers	
	Development of cooperation with domestic enterprises of oil and gas engineering	
	Development of cooperation with small and medium-sized businesses (oilfield services)	
	Collaboration with Asian R&D partners	
	Use of government mechanisms: development institutions, clusters, technology platforms, etc.	
	Other: ___________________________________	

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Evaluation of Pollutant Emissions into the Atmosphere during the Loading of Hydrocarbons in Marine Oil Tankers in the Arctic Region

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Abstract: Emissions of volatile organic compounds into the atmosphere when loading oil or petroleum products into tankers are strong environmental pollutants. Given the increase in oil transport by sea and the development of Arctic routes, humanity faces the task of preserving the Arctic ecosystem. Vapor recovery units can limit the emissions of volatile organic compounds. However, it is necessary to estimate the emissions of oil and petroleum products vapors. This article offers two methods for estimating emissions of volatile organic compounds. In the analytical method, a mathematical model of evaporation dynamics and forecasting tank gas space pressure of the tanker is proposed. The model makes it possible to estimate the throughput capacity of existing gas phase discharge pipeline systems and is also suitable for designing new oil vapor recovery units. Creating an experimental laboratory stand is proposed in the experimental method, and its possible technological scheme is developed.

Keywords: volatile organic compounds (VOCs); vapor recovery unit (VRU); oil loading; oil evaporation; arctic's protection; emissions assessment; available technologies

1. Introduction

Resource saving and the increasing requirements in environmental safety are a noticeable trend in the modern and world practice of transportation of hydrocarbons. Crude oil and oil product tankers emit Volatile Organic Compounds (VOCs) during the loading, transport, and discharging of their cargo. VOCs with a vapor pressure of more than 0.01 kPa at 239.15 K evaporate from the surface of crude oil in cargo tanks [1]. Approximately 2.4 million tons of VOCs, equivalent to about US$ 700 million, are lost each year during crude oil transport [2]. Volatile organic compounds emissions include propane (C_3H_8), butane (C_4H_{10}), pentane (C_5H_{12}), oxygen (O_2), carbon dioxide (CO_2), and small amounts of aromatic and sulfur-containing compounds. Under the influence of ultraviolet light and ozone, VOCs turn into dioxins [3]. Dioxins are environmental pollutants, and they are highly toxic to humans. VOCs also react with nitrogen oxides and form ozone when exposed to sunlight [4]. Ground-level ozone is one of the main components of urban smog [5]. The effects of ozone on a living organism are diverse. It causes morphological, biochemical, and functional changes in the body, significantly reducing its protective functions [6]. Besides, the opening of the mast riser on a tanker leads to significant losses of volatile hydrocarbons and an emergency shutdown of oil export due to an increase in the hydrocarbons concentration at the terminals above permissible values. For these reasons, it was decided to limit VOC emissions.

In 1997, the International Maritime organization created Annex VI of the MARPOL Convention, which entered into force in 2005. Annex VI describes measures to prevent air pollution, including VOCs, to provide terminals with facilities for receiving pollutants and state control. In addition, the Directive 2005/35/EC on pollution of ship sources and the imposition of fines for violations was adopted in the same year. Its goal was to tighten existing regulations to prevent the release of pollutants from ships. In particular, a protocol was adopted by a resolution of the Marine Environment Protection Committee, namely MEPC.176 (58), which entered into force on 1 July 2010 [7].

As global warming causes much of the area to melt, coastal countries have many opportunities [8]. The development of the Arctic coastline is especially important for the Russian Federation [9]. The Arctic route will shorten the route for ships by tendays compared to the Suez Canal. Cargo transportation statistics confirm this. In 2016, cargo traffic increased by more than 2.5 times compared to the previous year and amounted to 5.2 million tons. These facts indicate that the route is getting busier, and its usage is increasing exponentially [10]. The activities of the Russian Federation in the region can be traced in Figure 1.

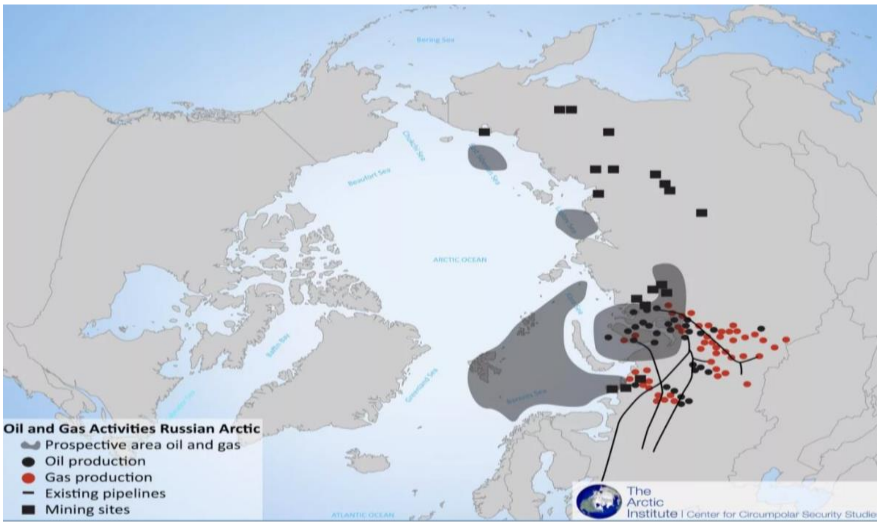

Figure 1. Russia's energy assets in the Arctic.

The sale of energy resources through seaports is one of the main export priorities of most oil companies, Russia, Canada, the USA, and the Middle East. The volumes of oil exports through sea terminals are steadily increasing. For example, at the sea terminal, the final point of the Eastern Siberia-Pacific Ocean oil pipeline, oil exports in 2010 amounted to 15.3 million tons, and in 2016, 31.8 million tons. Owing to the increase in shipment volumes, the loss of hydrocarbons from evaporation also increases. Therefore, the trend towards increasing the transport of oil and oil products and the development of oil and gas fields in the Arctic zone pose a new challenge for humanity. It requires developing methods to prevent the negative impact on the Arctic environment, which is so sensitive to anthropogenic impacts.

There is a need to monitor the Arctic zone state and control activities that may harm it [11]. To do this, you need to predict and assess possible emissions and develop measures to prevent VOC emissions into the Arctic region atmosphere.

Countries possessing unequaled mineral potential have a unique chance to improve efficiency in this sector and extensive emerging opportunities to improve labor productivity in the industry [12]. Key preconditions for this are adopting and implementing organizational and legislative solutions in parallel with digital technology [13].

Estimated data on energy resource loss indicate that the Russian economy loses annually approximately 500 thousand tons of oil on the journey from extraction to the end-user in the absence of a vapor recovery unit on marine transport and during loading. The greatest losses occur in the fuel and energy industry itself [14]. The combination of various cost-effective technologies can increase project economic stability and financial attractiveness, which is one of the main conditions for further large-scale development [15–18].

This paper aims to offer possible estimation and forecasting of VOC emissions into the atmosphere when loading hydrocarbons into tankers.

This paper is organized as follows: Section 2 describes the proposed methods for estimating VOC emissions to the atmosphere; Section 3 presents investigations with corresponding calculations and graphs; Section 4 gives the results of the investigations, and Section 5 presents the conclusions of this article.

2. Methodology

2.1. Analytical Method for Estimating VOC Emissions into the Atmosphere

The amount of VOC emissions can be predicted analytically. A mathematical model is proposed that describes the dynamics of gas flows when loading tankers. The model determines the pressure growth curve in the gas space of tankers. This model can be used to estimate or prevent possible VOC emissions to the atmosphere. The nonlinear differential equation is based on the method of solving Runge–Kutta–Felberg differential equations. The model can be used in the design of new vapor recovery installations and the optimization of existing ones.

2.2. Experimental Method for Estimating VOC Emissions into the Atmosphere

An experimental method for estimating emissions is also proposed. Creating a laboratory stand for vapor recovery allows identifying VOC emissions' actual values into the atmosphere when loading a tanker. This experimental apparatus has a purge air system. The use of a recuperator for the flow of working fluid after the expander and a pump at the expander's outlet connected to a multiplier, which makes it possible to retain the amount of volatile organic compounds and convert them into gas.

We found that only a few studies have discussed the VRU by considering the type of crude oil. For instance, a few studies have confirmed crude oil processing as one of their major sources of VOCs, e.g., U.S. crude oil [19–22], Alaska crude oil, and Canadian crude oil [23–25]. However, it was impossible to provide any relationships between the type of crude oil from these data due to the different analytical methods and existing uncertainties. Therefore, it appears that there is a lack of comprehensive experimental research on VRU concerning various types of crude oils and operating conditions (temperature, humidity, etc.). Another factor is the lack of enough information related to the initial stages of crude oil production (before refineries), in which highly volatile compounds may escape into the atmosphere due to lack of appropriate measures.

3. Case Study

3.1. Conceptfor Constructing a Mathematical Model of the Gasspace Dynamics of a Tanker

In the process of filling the tanker, oil is supplied with a flow rate of Q_i. The volume of the tanker's gas space changes, and the pressure inside the tanks P increases. The increase in pressure is caused not only by changes both in the volume of the gas space (GS) and by saturation of the GS with vapors of evaporating oil or petroleum product.

The movement of the gas-air mixture (GAM) with the flow of GAM occurs under the influence of the pressure drop between the tanker and the end point of the pipeline (pressure P_k), which removes the gas phase. In case the pressure exceeds the emergency value, the mast riser will open. GAM excess is diverted through the tanker's ventilation system to the mast riser with a Q_{mr} flow rate. Figure 2 shows a diagram of the displacement of hydrocarbon vapors when loading a tanker.

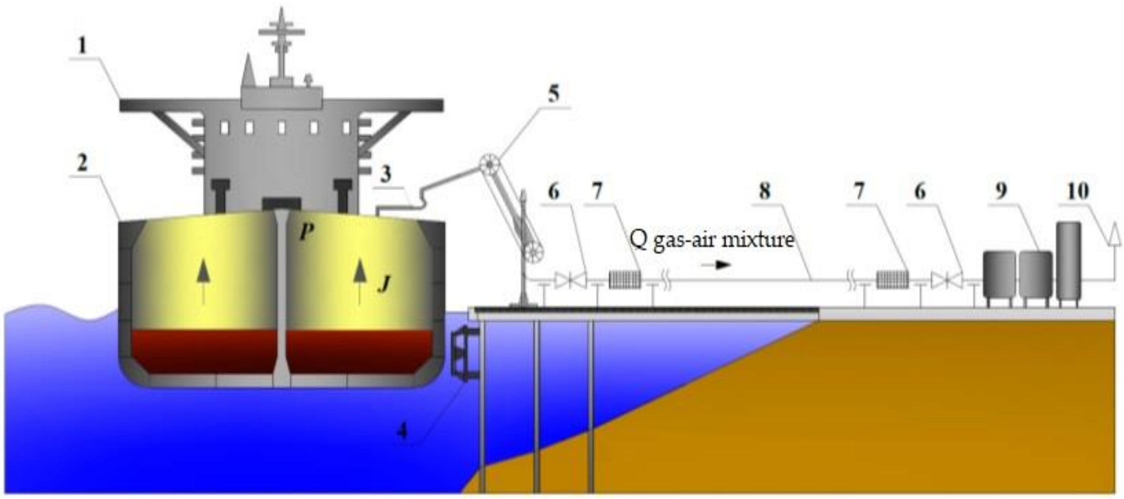

Figure 2. Diagram of hydrocarbon vapors displacement during tanker loading. 1—tanker; 2—double housing; 3—the manifold release of vapor; 4—node protection berthing facilities fender; 5—a stander removal of the gas phase; 6—shut-off and control valves; 7—detonation arrestor; 8—the pipeline of the gas phase; 9—VRU; 10—gas vent.

To optimize the operation of VRU and correctly assess the loss of hydrocarbons through the mast riser, there is a need to describe the dynamics of gas flows when loading tankers.

The GS of a tanker equation in differential form is:

$$\frac{dP}{dt}\cdot V + \frac{dV}{dt}\cdot P = \frac{dG}{dt}\cdot R\cdot T, \quad (1)$$

P—the pressure in the gas space of the tanker, Pa; t—the time from the beginning of loading, s; V—the volume of the tanker's gas space, m^3; G—the mass of steam-and-gas in the gas space of the tanker, kg; R—the gas constant, J/kmol·K; T—the steam-and-gas temperature, K.

The current value of the volume of the GS of the tanker can be noted from Equation (1), where the change in volume over time is equal to the flow rate of the injection with the opposite sign ($\frac{\mathrm{dV}}{\mathrm{dt}} = -Q_i$)

$$\frac{dP}{dt}\cdot\left(\frac{V_0 - Q_i\cdot t}{R\cdot T}\right) + \left(-\frac{Q_i\cdot t}{R\cdot T}\right)\cdot P = \frac{dG}{dt}, \quad (2)$$

V_0—the initial volume of the tankers as space, m^3; Q_i—volumetric flow rate of oil injection in the tanker, m^3/h.

The change in the mass of the steam-and gas in the gas volume of the marine tanker in Equation (2) is defined as the difference between the mass entering the gas volume as a result of evaporation per unit time and the mass flow rate of the gas phase that is discharged through the pipeline to the vapor recovery units [16].

$$\frac{dG}{dt} = J\cdot F - \frac{S\sqrt{P^2 - P_k^2}}{\sqrt{R\cdot T}\sqrt{2\cdot ln\left(\frac{P}{P_k}\right) + \lambda\frac{L_{eff}}{D}}}, \quad (3)$$

P_k—the pressure output in the pipeline of the gas phase, Pa; J—the intensity of mass transfer from the evaporation surface, kg/m^2·s; F—the surface area of evaporation, m^2; S—the line flow area of the gas phase, m^2; L_{eff}—the effective length of the gas phase pipeline taking into all local resistances, m; D—the diameter of the gas phase pipeline, m; λ—the coefficient of hydraulic resistance, dimensionless.

The mathematical model is made with the following assumptions:

(1) The inertance of the flow can be neglected due to the gas phase pipeline has a long length;

$$\lambda\frac{L_{eff}}{D} \gg 2{\cdot}ln\left(\frac{P}{P_k}\right) \tag{4}$$

(2) the gas constant is regarded as constant, R = const;
(3) the law of mass transfer during evaporation is accepted exponentially.

The law of mass transfer during evaporation from the surface of the filling oil is adopted as.

$$J = J_b{\cdot}e^{-\varepsilon\tau}, \tag{5}$$

J_b; J_e—flow density of evaporating oil respectively at the beginning and end of loading, kg/m^2·s; ε—the calculated coefficient equal to $ln\frac{J_e}{J_b}$, dimensionless; τ—the loading time equal to the ratio of the current time elapsed from the beginning of loading time to the total tanker ($0 \le \tau \le 1$), dimensionless.

Taking into account Equation (4), we obtain:

$$\frac{dP}{dt}{\cdot}\left(\frac{V_0 - Q_i{\cdot}t}{R{\cdot}T}\right) + \left(-\frac{Q_i}{R{\cdot}T}\right) = J_b{\cdot}F{\cdot}e^{-\varepsilon\tau} - \frac{P_k\sqrt{\left(\frac{P}{P_k}\right)^2 - 1}}{\frac{\sqrt{R{\cdot}T}}{S}{\cdot}\sqrt{\lambda{\cdot}\frac{L_{eff}}{D}}}, \tag{6}$$

Divide both sides of Equation (6) by $\frac{Q_i{\cdot}P_k}{R{\cdot}T}$:

$$\frac{dP}{dt}{\cdot}\left(\frac{V_{eff} - Q_i{\cdot}t}{Q_i{\cdot}P_k}\right) - \frac{P}{P_k} = \frac{J_b{\cdot}F{\cdot}R{\cdot}T}{Q_i{\cdot}P_k}{\cdot}e^{-\varepsilon\tau} - \frac{S\sqrt{R{\cdot}T}}{Q_i{\cdot}\sqrt{\lambda{\cdot}\frac{L_{eff}}{D}}}\sqrt{\left(\frac{P}{P_k}\right)^2 - 1}. \tag{7}$$

The following dimensionless groups are introduced:

$$\frac{P}{P_k} = y, \tag{8}$$

$$\frac{J_b{\cdot}F{\cdot}R{\cdot}T}{Q_i{\cdot}P_k} = \psi \tag{9}$$

$$\frac{Q_i{\cdot}\sqrt{\lambda{\cdot}\frac{L_{Eff}}{D}}}{S\sqrt{R{\cdot}T}} = \theta, \tag{10}$$

$$\frac{t}{t_{end}} = \tau \tag{11}$$

Dimensionless groups have the following physical meaning:

y—the dimensionless pressure ratio, ψ—characterizes the contribution of evaporation to the overall dynamics of pressure growth in the gas space of the tanker, θ—characterizes the contribution of hydraulic resistances to the dynamics of pressure growth in the gas of the tanker, τ is the injection time.

Thus, we get the generalized differential equation in dimensionless parameters for studying the dynamics of pressure growth in the tanker's gas space.

$$\frac{dy}{d\tau}{\cdot}(1-\tau) = y + \psi{\cdot}e^{-\varepsilon\tau} - \frac{\sqrt{y^2 - 1}}{\theta}. \tag{12}$$

This Equation (12) is a first-order nonlinear differential equation. The nonlinear differential equation and the algorithm are based on solving Runge–Kutta–Felberg differential equations of orders 4 and 5 (depending on the conditions of adaptation of the solution to its rate of change).

A calculation of the evaporation was carried out to study the influence of various factors on the dynamics of pressure changes in tankers' gas space. The evaporation calculation was solved by Equation (3) for various values of the dimensionless parameters ψ and θ. Figure 3 shows a graph of changes in the dimensionless pressure drop for different values of the parameter ψ, for θ = 0.3 and ε = 0.8. Figure 4 shows a comparison of the results of modeling the dynamics of pressure changes in a tanker's gas space with experimental data. This calculation shows a quantitative and qualitative determination of the dynamics of pressure growth in a tanke's gas space.

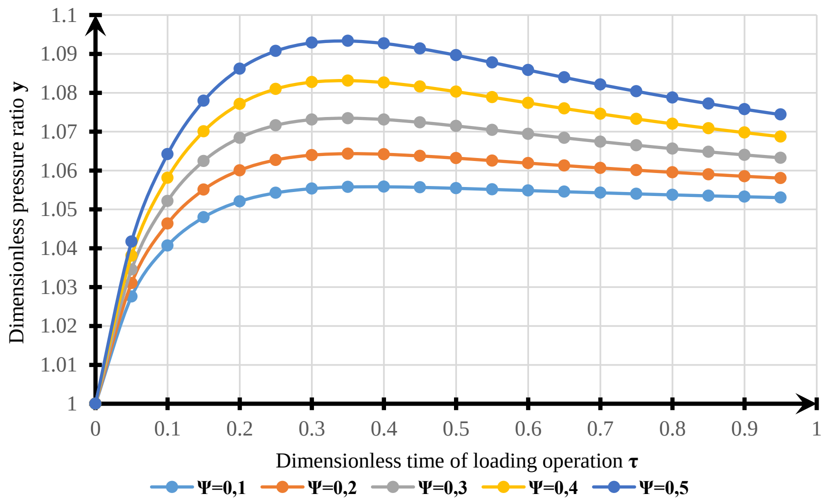

Figure 3. The graph of changes in the dimensionless pressure for various parameter Ψ, θ = 0.3; ε = 0.8.

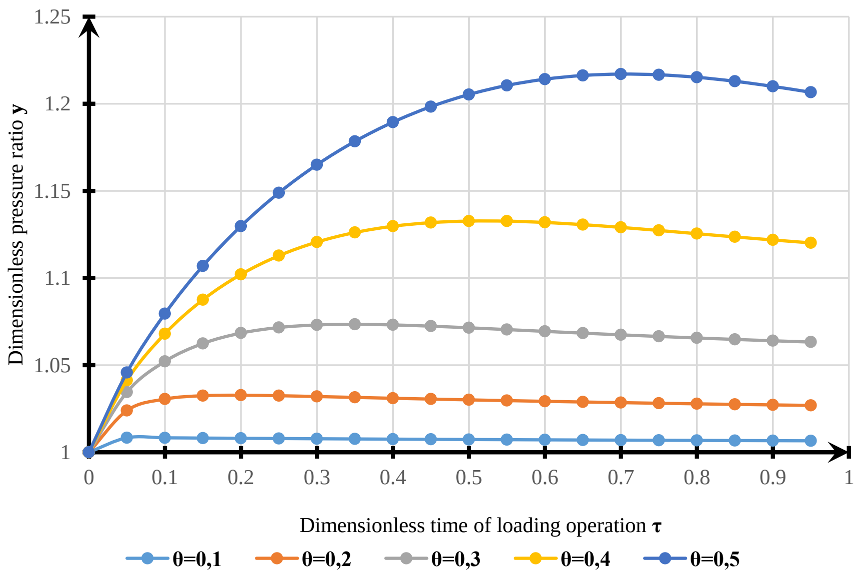

Figure 4. The graph of changes in the dimensionless pressure for various parameter θ, for ψ = 0.3 and ε = 0.8.

The dimensionless parameter θ, which characterizes the system's hydraulic resistance, has a significant impact on the dynamics of pressure growth in the gas space of a tanker.

The results obtained were compared with experimental data for more than 200 tankers. The suitability of the developed model was evaluated on the example of the SOPHIE SCHULTE tanker. The general view of the tanker is shown in Figure 5. The technical specifications are shown in Table 1.

Figure 5. General view of the SOPHIESCHULTE tanker.

Table 1. Technical characteristics of the SOPHIE SCHULTE tanker.

Parameter	Value	Unit
Deadweight	115,583	tons
Dimensions	241 × 44	m
Method for inerting GS	exhaust gases	–
Pressure of saturated oil vapors on the raid	52.1	kPa

A comparison of simulation results with experimental data was performed. Table 2 shows a comparison of modeling the dynamics of pressure changes in the tanker's GS with experimental data.

Table 2. Comparing the results of modeling the dynamics of pressure changes in the tanker's GP with experimental data.

№	The Current Time from Beginning of Loading, h	Experimental Data on Pressure in the Tanker's GS, Pa	Pressure in the Tanker's GS Calculated by Equation (12), Pa
1	0	101,815	101,815
2	0.41	102,595	105,124
3	1.08	104,365	105,612
4	1.41	109,215	107,570
5	2.08	110,645	109,866
6	2.41	112,355	110,511
7	2.58	112,455	110,761
8	3.41	111,035	111,443
9	3.91	111,225	111,580
10	4.41	110,835	111,602
11	5.41	110,445	111,468
12	6.41	110,395	111,236
13	7.41	110,345	110,982
14	8.41	110,495	110,730
15	9.41	110,235	110,487
16	10.41	110,495	110,253
17	10.91	110,385	110,139
18	11.41	107,005	106,389
19	11.91	108,325	106,309
20	12.91	106,075	104,007
21	13.33	101,325	101,325

In addition, the results of modeling according to Equation (12) and experimental data on changes in the dynamics of pressure changes in the tanker's GS are shown graphically in Figure 6.

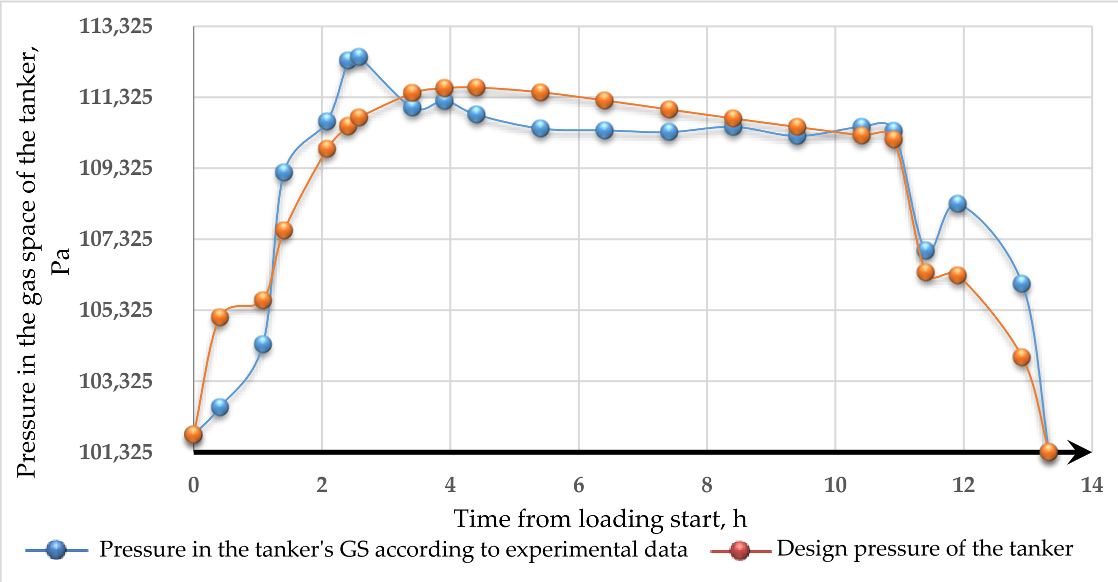

Figure 6. Results of modeling the dynamics of pressure changes in the tanker's GS and experimental data.

From Figure 6, the developed model allows us to correctly determine the dynamics of pressure growth in the tanker's gas space, both quantitatively and qualitatively. Some inconsistency of the model in changing injection modes with experimental data is explained by complex transitional processes, which can be accounted for using smoothing functions and there is some scientific interest for further work in this direction.

3.2. Laboratory Stand Concept for Vapor Recovery Unit

The sale of energy resources through seaports is one of the main export priorities of many oil companies [17]. This approach allows not only to diversify sales markets but also to avoid export quotas for transportation through the pipeline system. One of the vital problems is the loss of transported hydrocarbons. Because of this, enterprises incur ongoing costs for taxes for emissions of pollutants, lose valuable products, and cause huge damage to the environment [18]. In world practice, these problems are solved by the introduction of vapor recovery units (VRU). Several technologies are available to treat volatile organic compounds such as direct combustion, absorption, adsorption, membrane separation, compression, and condensation. Since VRUs cannot capture all VOCs, it is necessary to determine the effectiveness of installations experimentally before implementing them on terminals.

It is proposed to use a laboratory stand for VRUs to measure the actual values of VOCs emissions. The stand should contain vapor recovery technologies that are most suitable for the conditions of marine terminals that is, for large volumetric flow rate of loading oil or oil products in a tanker. The following technologies are suitable for this purpose:

- adsorption;
- absorption;
- condensation.

The development of a laboratory stand will solve the existing problems by evaluating the effectiveness of vapor recovery technologies and VOC emissions. The experimental stand will allow us to determine a set of parameters of the VRUs and optimize their operation.

The stand will allow monitoring changes in the terminals' state and the ability to control this process in the laboratory. This method allows predicting VOC emissions in the Arctic zone with the specified parameters.

Within the framework of this theory, a technological scheme for installing a laboratory stand was developed that is shown in Figure 7. Oil vapors are blown from tanks T1 and T2 through a detonation fire barrier, a drop breaker. Then they fall into the column of one of the technologies considered. The stand demonstrates the above-described vapor recovery technologies. After that, the undetected vapors are refined in a flow chromatography and bleed through a gas vent stack. The shut-off and control valves are controlled independently using a programmable logic controller (PLC). External modules connected to the PLC perform the role of collecting and converting information from all sensors. Then the data are processed and stored for further analysis.

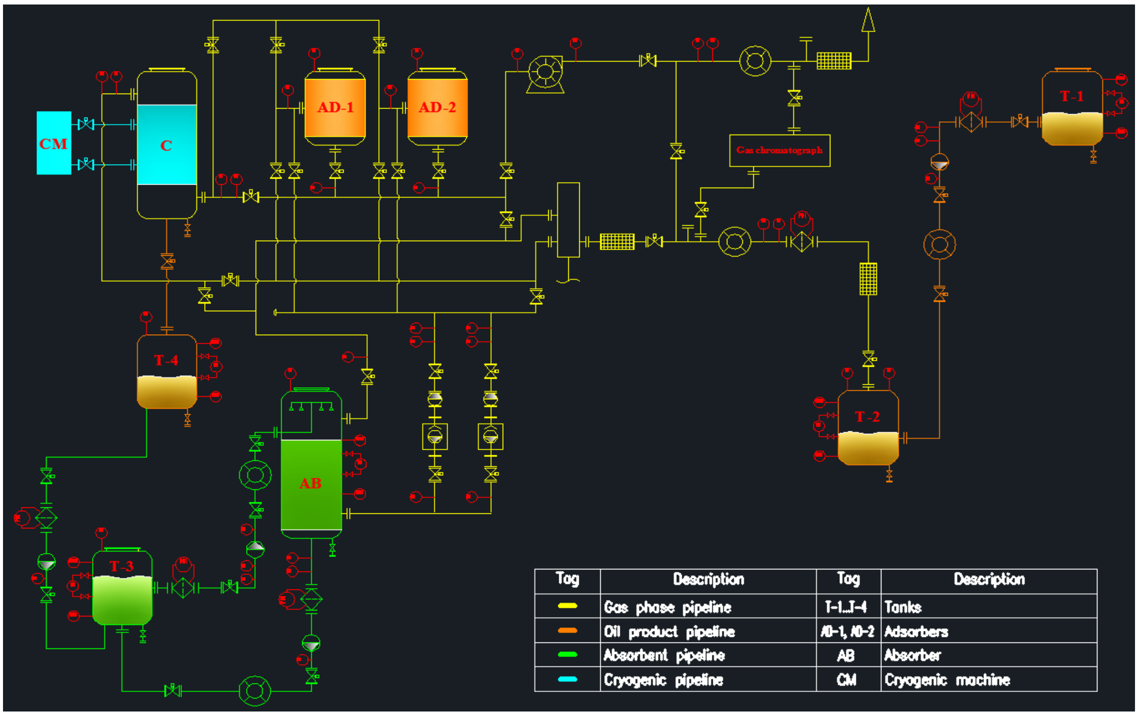

Figure 7. Flow chart of experimental apparatus (designed by Saint-Petersburg mining university).

4. Results

1. The graphs of changes in dimensionless pressure for various parameters in Figures 5 and 6 indicate that the most significant influence on the dynamics of pressure growth in the tanker's gas space is exerted by the hydraulic resistance of the gas drainage system.
2. The model obtained can be used for estimating VOC emissions when hydrocarbons are loaded into a tanker. The results of modeling the dynamics of pressure changes in the tanker's GS with experimental data allowed us to determine the calculation error. The standard error of the model is 1215 Pa. Complex transitional processes explain the discrepancy of the model in changing the injection modes, and the account of re-existing processes can be made using smoothing functions.
3. An experimental method for estimating vapor emissions can be achieved by creating a stand in the laboratory, using the technological scheme developed in this work.

5. Conclusions

Regulation of VOCs emissions becomes mandatory, and the VOCs recovery system can provide solutions to the requirements for loading crude oil. Taking into account the world's concern for sustainable development and the desire for environmental safety in oil transportation, especially in the Northern seas of the Arctic region, methods for estimating and preventing VOCs emissions were proposed, that are:

1. A mathematical model was constructed that adequately describes the dynamics of gas flows during tanker loading. The results obtained were compared with the experimental data on the

example of loading the SOPHIE SCHULTE tanker. Most of the error scans explain transitional processes when loading the tanker. Transitional processes are of some scientific interest for further work in this direction.

2. The developed model can be used for estimating VOCs emissions. It also allows the evaluation of the capacity of existing pipeline systems for the removal of the gas phase and the design of new installations for the recovery of oil vapor. This would reduce emissions of VOCs and increase the security of the Arctic region's ecosystem. It is also important to create a laboratory stand for an experimental method for estimating VOCs emissions and the effectiveness of the VRU.
3. The technological scheme of a possible laboratory stand for vapor recovery was developed, which can evaluate the efficiency of the VRU of adsorption, absorption, and condensation technologies.

The obtained calculations of the experimental setup describe the dynamics of gas flows when loading a marine tanker. The results were compared with the experimental time using the example of an operating marine terminal.

The unique features of the conditions of the polar regions and, in particular, the Arctic region, such as an isolated location, impassable roads, extremely harsh climate, put forward very specific requirements for equipment, organization of operations, and training of personnel. Despite the high level of attention of oil companies to environmental safety, the problem of capturing oil vapor when loading tankers remain open to many existing and planned oil terminals. Therefore, humanity must continue to seek solutions to the problem of VOC pollution in the environment.

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Integrating Real-Time Monitoring Data in Risk Assessment for Crane Related Offshore Operations

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Abstract: The oil and gas sector is one of the most dangerous and stringent workplaces, due to the hazardousness of materials involved as well as the critical tasks that workers have to perform. Cranes are widely used in this sector for several activities. A wrong load lifting or handling often is due to a limited visibility of working area and could bring to severe accidental scenarios, for this reason safety of these operations becomes of paramount importance. The use of safety devices, that provide an augmented vision to the crane-operator, is essential to avoid potential accidents, moreover risk analysis could benefit from the acquisition of real time information about the process. This work aims to extrapolate and adapt dynamic risk assessment concepts for crane-related operations of a typical oil and gas industry by means of the support of safety devices. To achieve this objective, a set of risk indicators, reporting continuous information about the operations that are carried out, will be defined; successively, a technique of aggregation of these indicators will also be applied with the aim to update the frequency of critical events by a proper Risk Metric Reduction Factor that accounts for the effect of the use of safety barriers.

Keywords: dynamic risk analysis; offshore oil and gas; crane operations

1. Introduction

The oil and gas sector is one of the most dangerous and stringent workplace as inherent hazards are difficult to deal with at times. This is due to the hazardousness of materials involved as well as the critical tasks that workers have to perform. The use of cranes in this field is common for several activities, such as moving equipment, maintenance activities, management services for offshore platforms, etc. Therefore, safety and performance of lifting operations become of paramount importance, given the evidence that a wrong load lifting or handling could bring to severe accidental scenarios such as fires, explosions, and toxic dispersions [1]. Particular attention is paid to Floating Production Storage and Offloading (FPSO) platforms, where risk is related to the handling of heavy loads from and to supply vessels, barges, or semi-submersibles. While performing such high hazards operations, safety cannot be ensured by design alone, as it also depends on human skills, maintenance personnel and inspectors, as well as the numerous technical parameters relating to the crane and its operating environment [2]. As analyzed by several authors [3,4], the limited visibility of the working area is a relevant cause contributing to the occurrence of accidents in crane-related operations, which usually involves both loads and objects located in the workspace (i.e., workers or other close equipment). A list of examples of this type of accident, from the oil and gas sector, is given in Table 1. These accidents have been collected worldwide [5,6] and a brief description for them is also provided. Accidental reports highlight that, in addition to the limited visibility, sometimes also a wrong task execution contributed to the occurrence of accidents. The use of safety devices that provide an augmented vision to the crane-operator is essential to avoid potential collisions due to a hindered view of the workspace [7]. Risk analysis could benefit from the use of such devices, because the acquisition of real time information about the process can be correlated to the safety. The advantages, derived from real-time monitoring and data acquisition, are introduced in the following.

Table 1. Crane-accidents due to a partially or totally hindered view of the workplace.

Year	Place	Description
1999	Gulf of Mexico	A crane-operator was moving a bundle of drill pipes when he struck a section of handrail. Such section was knocked out of its mounting sockets and fell down striking a worker on the shoulder. The blow knocked him down and he struck a welding machine with his head [8].
2013	Gulf of Mexico	An accident was due to a lack of adequate communication with the signal man during a blind lift operation that involved offloading equipment from a motor vessel to the platform. The event caused the injuring of a worker [9]
2015	US	A misunderstanding or an errata communication was the cause of a crane accident, occurred in an offshore platform during the relocation of two joints of damaged production tubing on the rig's main deck. Injured workers were recorded [9]
2016	Gulf of Mexico	A crane crew was conducting a blind crane lift from the safe welding area/production deck to the pipe rack. This event caused an injured worker [9]
2017	Gulf of Mexico	An accident, occurred in an offshore company, was due to a human error. A worker was severely injured. The investigation reports that the crane-operator could not see the rigger on the cellar deck, communications with rigger were made by radios. As the load was being lifted, it came in contact with a piece of channel iron. The channel iron was located behind the load represented by a tool house, approximately 3 m above the deck connected to a structural member [9]
2016	North Dakota (US)	A worker lost his life as he was struck by the boom during the replacement of a pipeline [5]

Paltrinieri and Khan [10] state that it is important to recognize small deviations from normal operability for better management of process safety and accident prevention. In fact, they believe that, acting on these, the chain of events would break and lower the probability of associated impacts. This can be extrapolated to crane-related operations. As an example, if one imagines a load lifting along a trajectory, a deviation could be a small displacement with respect to that trajectory, i.e., a typical event in which the crane-operator fails in exactly quantifying the displacement and that could lead to a collision of the load with an obstacle present in the workspace. Therefore, the early identification of a small deviation, by using a visual guidance device, is a useful element for accident prevention, in particular if it occurs in a workplace where hazardous substances are handled.

Dynamics Risk Analysis (DRA) approaches allow improving decision-making and supporting critical risk communication [11–13]. The integration of real-time monitoring data in risk assessment offers the opportunity to achieve a more effective control of activities in the workplace in view of worker's safety, thus DRA methods can be particularly useful to manage hazards associated with crane-operations (i.e., prevention of collisions and the timely implementation of protective actions). DRA is mainly based on the use of models integrating time-dependent parameters, which affect both frequency and consequence of accidents [14]. Its use is widespread in the management of several risk typologies, i.e., environmental risks due to marine oil spills [15–17], risks due to the use of toxic substances in terrorist actions [18], industrial risk due in operating chemical [19,20], environmental pollution from heavy off-road vehicles [21], etc. In recent years, Khan et al. [22] and Villa et al. [23] discussed research trends in using dynamic risk analysis and provided a review about methods and models developed for process safety and risk management. Tools providing real time monitoring of safety have also been proposed, as an example Kanes et al. [24], based on pre-identified risk factors and process safety related data, quantified increases in risk level in oil and gas industry by using Bayesian Networks. Dynamic risk assessment techniques based on proactive indicators, such as those suggested by Paltrinieri et al. [25], Scarponi et al. [26], Scarponi and Paltrinieri [27], can bring additional benefits, since risk analysis is supplemented by information related to early warnings of unwanted events. The integration of a set of collected indicators may provide risk assessment with dynamic and proactive features. Data collection and processing, for the purpose of DRA, take advantage of information technology. Paltrinieri et al. [25] classified dynamic risk assessment techniques based on proactive indicators in four levels by referring to the basic theory and provided results. The first level concerns the use of safety indicators and takes into account the effect of technical, human, and organization factors. The second level is related to the use of risk indicators, where the application of risk models is needed. The third level refers to the application of techniques for frequency updating. Finally, the fourth level concerns the use of techniques for the aggregation of data provided by indicators.

This work aims extrapolating and adapting DRA concepts for crane operations carried out by the support of safety devices. To achieve this objective, a set of risk indicators, reporting continuous information about the operations carried out in a typical oil and gas industry, is defined. The dynamic approach for risk assessment is based on the application of the bowtie method. The paper is structured as follows. In Section 2, the description of the proposed methodology for the dynamic risk assessment is given. It integrates risk indicators for the load lifting and handling in the bowtie approach; such indicators are derived by means of the Health and Safety Executive (HSE) approach [28]. Section 3 shows the description of a case study from the oil and gas context in which the application and validation of the approach is carried out. Section 4 reports the results obtained from this study. Finally, the conclusions of the work are presented in Section 5.

2. Methodology

The proposed methodology encloses dynamic features into the risk assessment procedure with respect to the conduction of load lifting or handling by using cranes in the oil and gas sector. Such an approach is schematized in Figure 1. The main steps are:

1. Definition of a set of appropriate risk indicators analyzing the hazard due to the interaction between the normal activity of the plant and the operations made by cranes;
2. Calculation of indicators;
3. Application of the bowtie method for frequency assessment;
4. Aggregation of risk indicators;
5. Frequency updating;
6. Data collection for the calculation, review, and update of indicators.

The HSE approach [28] has been used to derive risk indicators. In their derivation, the use of the Visual Guidance System (VGS), as an innovative safety device to prevent accidents due to collisions, has also been assumed in the form of a safety barrier. The acquisition of information about the load trajectory, prevented collisions and near-misses allows for a continuous updating of risk indicators. As mentioned above, the reason suggesting the introduction of the VGS is one of the most common situations leading to crane accidents, in which the operator has partially or completely hindered view of the workspace and he/she needs to be supported by an intermediary in navigating the load [1]. Given that the HSE approach is used to derive indicators associated with the chemical process safety, here the main innovation concerns the use of the same approach to derive indicators for crane-related operations accounting for the hazardousness of substances used in the workplace.

The application of the bowtie allows quantifying the frequency of occurrence of hazard scenarios. Once safety barriers and a number of risk indicators at the facility or process level have been defined, these must be hierarchically combined to reflect the effects of the success of each barrier in reducing the risk. This combination is named "aggregation". The aggregation of risk indicators allows continuously updating frequency, again by means of the application of the bowtie approach. Data collection for the definition of indicators and their calculation is used to review and update them.

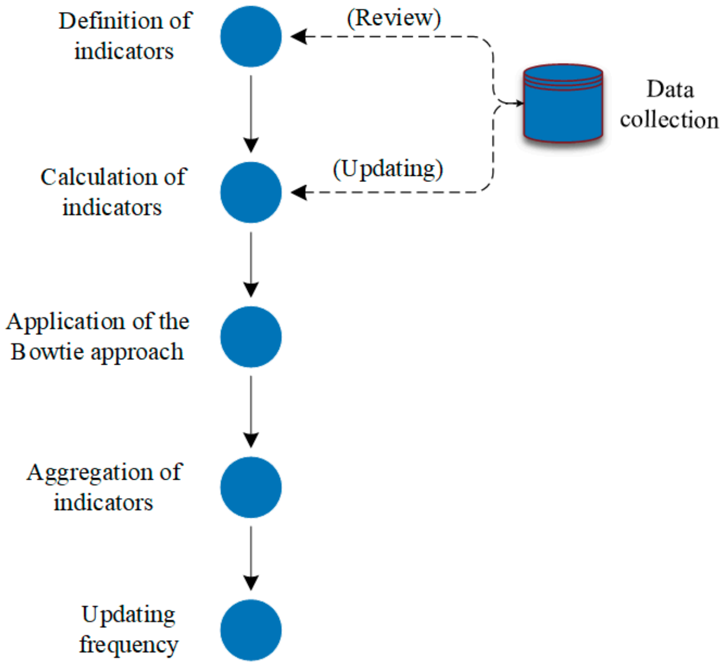


Figure 1. Scheme of the methodology proposed.

2.1. *Definition and Calculation of Indicators*

The methodology of HSE [28] is based on the development of lagging and leading indicators for facilities/processes. A lagging indicator represents a form of a reactive monitoring of the effectiveness of a system adopted to control risk, given that they provide feedback after the occurrence of a negative event; whereas, a leading indicator represents a form of proactive monitoring of the effectiveness of the same system, by the provision of a feedback before an incident occurs.

Each facility/process has one or more systems to prevent, control and mitigate major accidents; these are the so-called safety barriers or barrier systems or simply barriers [29]. Operational procedures and inspections are also considered safety barriers by the MIRAS methodology [30]; on the contrary, the HSE refers only to technical systems (named risk control systems) that are associated with the previous identified hazard events [28]. Figure 2 gives a schematic view of the approach used to derive risk indicators for the prevention and mitigation of accidents due to the interaction between chemical processes and the load lifting made by cranes. It is a modification of the HSE approach that, being inspired by MIRAS methodology, includes operational procedures and uniforms terminology by replacing risk control system with safety barriers [31]. By referring to Figure 2, the main steps to develop indicators are the following (to be applied for each safety barrier): 1) identification of the scope of indicators; 2) setting of lagging indicators; 3) setting of leading indicators; 4) selection of the most relevant indicators for the activity under consideration. The procedure also includes data collection and the revision of developed indicators, these are not mentioned in this section as included as a further step in the whole procedure of Figure 1.

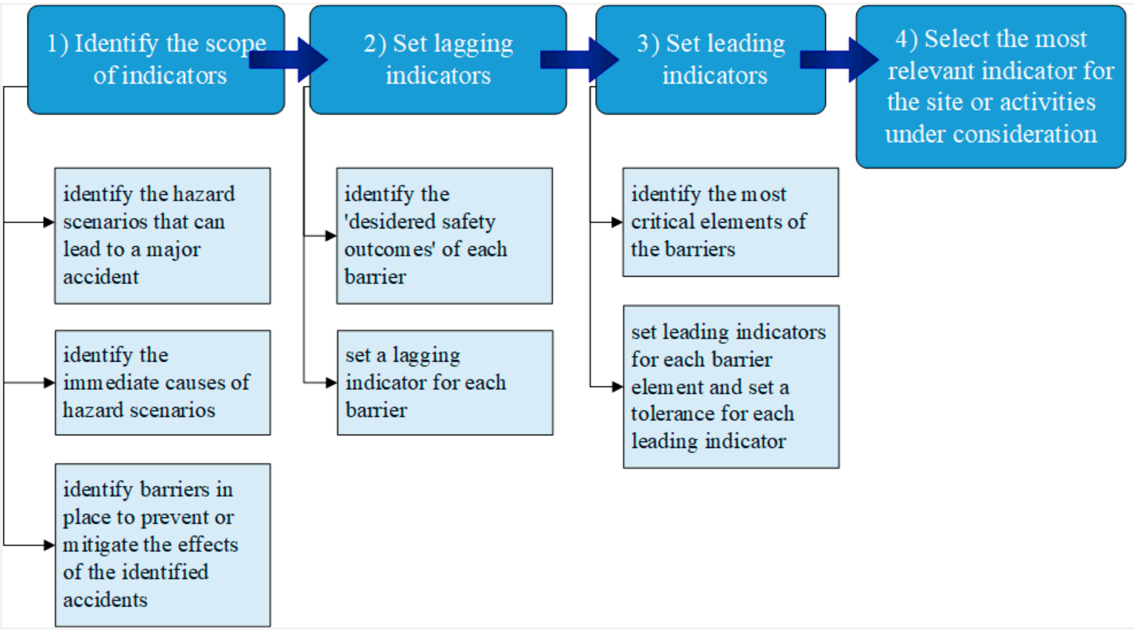


Figure 2. Main steps of the modified HSE approach for the development of risk indicators.

The first step of Figure 2 is the definition of the scope of indicators (step 1) that, in this case, is the prevention of some hazard scenarios. For this reason, the description of the evolution of the event is necessary to identify potential scenarios leading to major accidents. The HSE methodology suggests focusing on the primary failure mechanism and paying attention to data recorded about past near-misses and accidents. The description of hazard scenarios allows the definition of the safety outcomes that the plant management would like to reach. Thus, a list of barriers preventing or mitigating the consequences of each hazard scenario has to be drawn. A desired safety outcome represents the success of a barrier; therefore, it should be clearly identified in terms of success or failure. A set of lagging indicators for each barrier (step 2) highlights whether the desired outcomes are actually achieved. After, a leading indicator for each safety barrier reveals if it is operating as desired, i.e., it indicates the achievement of the goal, which is preventing the undesired event (step 3). To complete this step, two furthers activities are suggested by the HSE approach: (i) to set a range of tolerance for each indicator, warning the analyst in case of deviations from normal performance; (ii) to revise indicators, based on the clear evidence that two indicators from the same barrier do not have to give conflicting results. Finally, the selection of the most relevant indicators should be made to help the manager to have a simpler and immediate comprehension of the risk level at the site (step 4). This will be better described below.

Figure 3 shows how the HSE method has been adapted to include potential interference between the crane operability and the normal activity for the plant. The first step of the modified approach includes the hazard investigation. The load lifting/handling with the crane could generate collisions, impacts, or other hazardous events, which lead to losses of containment and related cascading events. The identification of proper safety barriers and the set of proper indicators (lagging and leading) for each of them represents the following step.

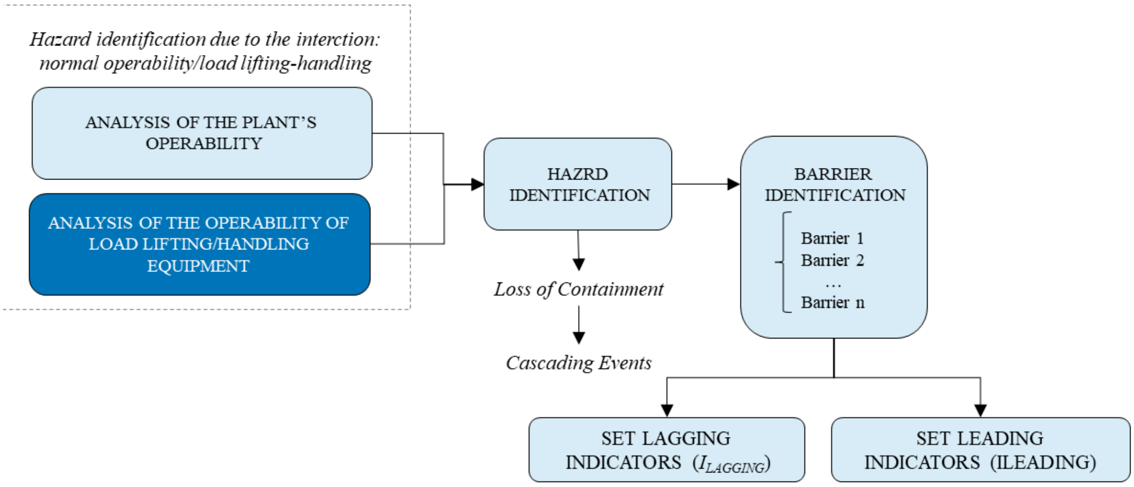


Figure 3. Methodology for the development of indicators for load lifting/handling in oil and gas industry.

2.2. Application of the Bowtie Approach

A bowtie is a risk evaluation technique, based on the use of a scheme that permits to analyze and demonstrate causal relationships. It is an easy graphical representation (Figure 4) that visualizes events which must be dealing with [32] and indicates all plausible accidental scenarios around a certain hazard. It also allows identifying control measures to manage such scenarios and the ways in which they fail. All bowties converge in a central event which is usually defined as the loss of control. This event represents the Critical Event (CE) or Top Event. On the left side of the CE, the event evolution is described by the Fault Trees Analysis (FTA) and, on the other side, by the Event Tree Analysis (ETA). Both of them are enriched with barriers.

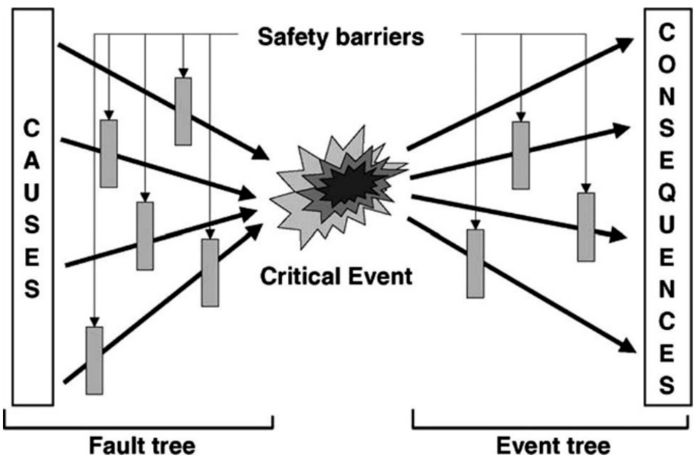


Figure 4. Generic bowtie (source: [33]).

Being inspired by the ARAMIS project [30], the use of the bowtie methodology is promoted in this work to investigate critical events in order to identify their initial causes and consequent scenarios. Therefore, the actual procedure consists of the following steps: initially, the definition of the worst accidents that likely occur at the installation, by assuming that no safety barriers are installed (Methodology for the Identification of Major Accident Hazards, MIMAH approach); second, the analysis of the influence of safety barriers adopted by the company, which allows defining the Reference Accident Scenarios, representing the real hazardous potential of the installation (Methodology for the Identification of Reference Accident Scenarios, MIRAS approach). Safety barriers and related indicators represent essential elements in reducing the frequency of occurrence of undesired events. If such indicators are continuously updated, a simultaneous frequency updating is achieved.

The FTA of Figure 5 represents the left part of the bowtie. It has been developed for a loss of containment of a hazardous substance from a tank, which could occur during the activity of the plant or due to an interference with the crane operability. Some barriers (B) have been included to prevent, control or mitigate major accidents due to the loss of containment, these are summarized below:

1. Plant operating procedures (B1)-set of procedures that regulate plant operability.
2. Crane operating procedures (B2)-set of procedures that regulate the crane operability.
3. Inspection and maintenance procedures (B3)-procedures inherent inspections and maintenance.
4. Work permit procedures (B4)-procedures to perform certain tasks that are outside the routine activities, e.g., maintenance operations.
5. Emergency procedures (B5)-set of procedures that must be implemented during an emergency.
6. Visual Guidance System VGS (B6)-innovative tool, developed by Ancione et al. [34], supporting crane-operators in situation in which they have a hindered view of the workspace during the load lifting/handling.
7. Plant design (B7)-criteria adopted to design measures controlling or mitigating potential hazard scenarios.

In Figure 5, the breach on the shell of the vessel, containing a hazardous substance, brings to a loss of containment (LOC), representing the hazard scenario here analyzed. Going backwards, it is possible to investigate direct causes leading to this event and, further on the left side of the graph, their initial causes. The scheme is divided in two blocks highlighted by grey dashed lines. The first block (upwards in the figure) shows the branches of the FTA concerning the plant operativity, whereas the second one (downwards in the figure) analyses the crane operation. The main barriers, to avoid the occurrences of the LOC, are given. There are many causes (branches) that could lead to the hole on the vessel, several are also their initial events; the barriers, that allow preventing each event, are indicated below in brackets.

The branches, associated with the plant operability, have been developed as discussed in the following. An overpressure could be generated by filling the vessel beyond the normal level or its threshold limit of pressure (design value), depending on if it is liquid or gaseous; this excessive transferring of substance, in turn, could be triggered by a technical failure of the control system (B5) or a design error (B7) and a human error (the operator does not act the manual actuator—B1). The occurrence of a brittle rupture has to be included given the nature of the material inside the vessel, which is due to a brittle structure, the failure of inspection, and maintenance procedures (B3) and an impact on the structure. An overloading could be caused by a natural phenomenon (as snow, ice, etc.—B7) or by a load on the roof of the vessel (B7) or even by a failure of its support (B3, B7). High amplitude vibrations have to be included due to natural causes (earthquakes—B7) or are due to motors vibrations (B7) or defects or maintenance errors, etc. (B3). A dilatation of the material would be the effect of a fire coming from a neighbor equipment (domino effect) or from the outside of the facilities (B5), it could be also the effect of a hot work or a wrong execution of a special work (B4). A mechanical rupture is due to a shear stress (which represents a mechanical stress due to natural causes or process anomalies) and the failure of the plant design procedure (B7). The use of wrong material for the equipment manufacturing could be the consequences of a design error or a human error (wrong material ordered, delivered, etc.); it could also be the consequences of the use of a bad quality material during the construction, which has previously been delivered or resulting from storage (or transport) conditions or from a manufacturing error (B7). An inappropriate sizing could be due to a design error (B7). An inappropriate assembling could be due to a wrong assembling procedure that means a design error (B7) and a human error due to a not respected assembling procedure (B7). An impact could be caused by missiles originated by domino effects (B7) or by moving an object close to the facilities (B7).

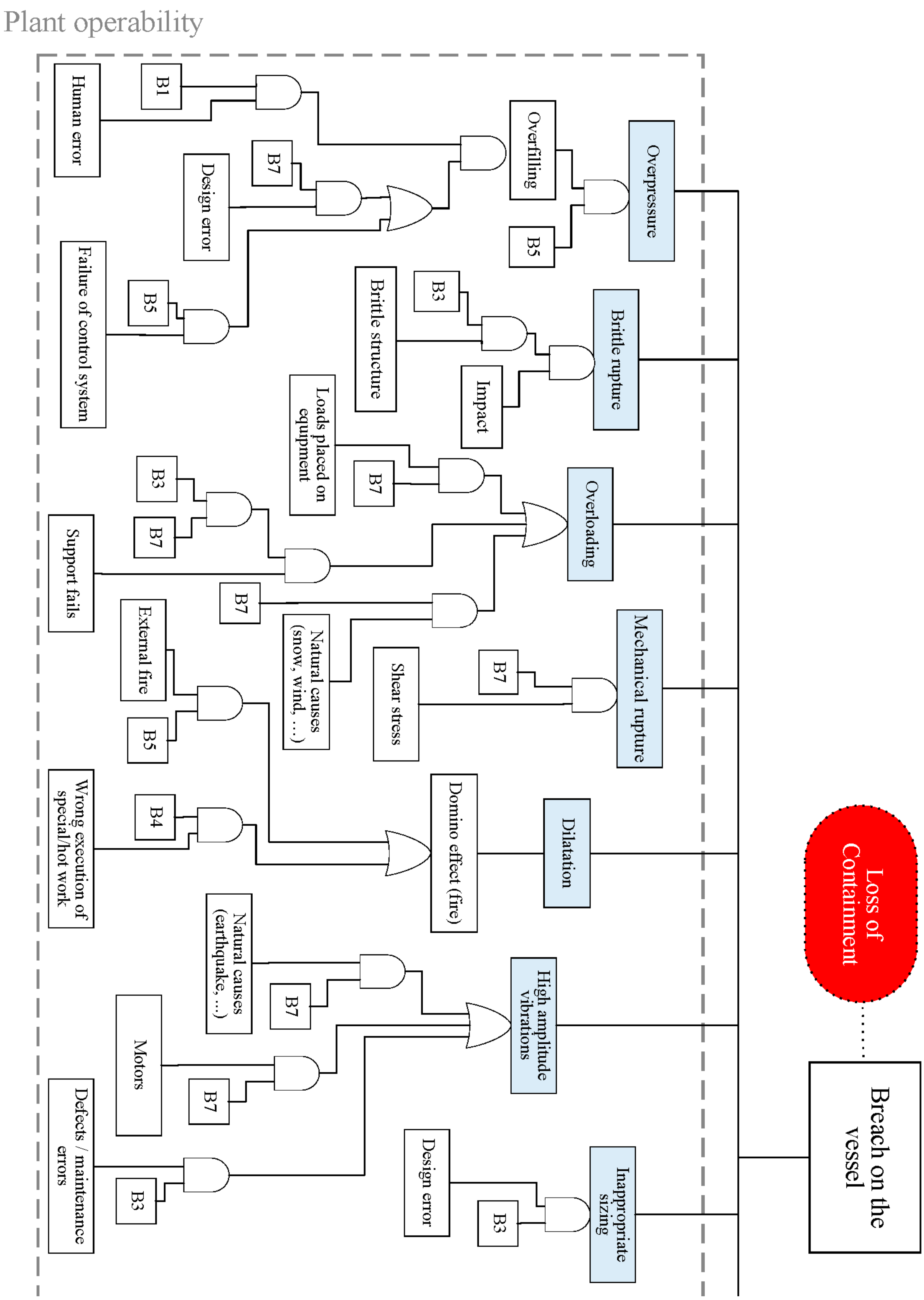


Figure 5. *Cont.*

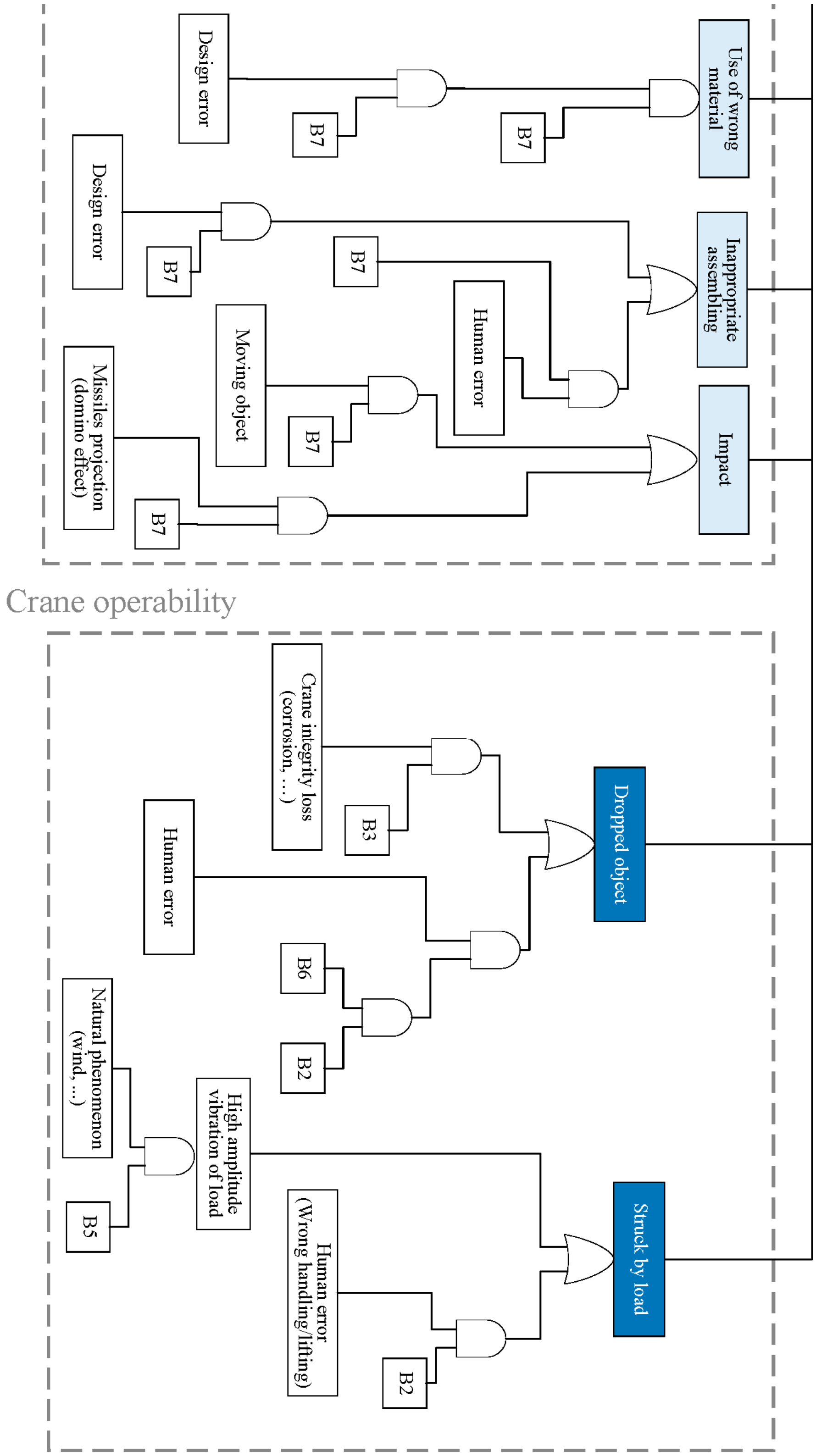


Figure 5. Fault Tree Analysis developed for the loss of containment from a vessel integrity.

The branches, associated with the interference between the crane operations and the plant operability, have been developed by considering two potential events, i.e., dropped object and struck by load. An object could drop from the crane due to a loss of integrity of a part of the equipment, caused by deterioration mechanisms (i.e., corrosion, etc.—B3) or a human error, such as distraction, wrong communication, etc. (B2, B6). The vessel could be struck by the handled load or a moving part of the crane (boom, hook, etc.); related causes are human error (wrong communication, distraction, hindered view, or other—B2, B6) or high amplitude of load vibrations, due to a natural phenomenon (i.e., strong wind—B5) or a wrong handling made by the operator (B2, B6).

Importance of Barriers

After the definition of the barriers and the set of indicators associated with them, the importance of each barrier should be evaluated in order to select the most relevant in term of risk reduction. This is obtained by a sensitivity analysis, which examines how the results of the model vary due to changes of individual variables, i.e., input parameters (failure rates, probabilities, repair times, etc.), and assumptions in the analysis and structure of the model. The sensitivity analysis allows identifying elements that have the highest impact on the risk and, thus, to study the effect of proposed risk-reducing actions.

A sensitivity model is the Birnbaum's measure I^B [35], which calculates the relative importance of a basic event k in a fault tree (in this case a barrier's failure):

$$I^B(k|t) = \frac{\partial P_{CE}(t)}{\partial P_k(t)} \text{ for } k = 1,\ 2, \ldots,\ n \tag{1}$$

where P_{CE} = probability of the critical event CE; P_k = probability of an input event k; t = time.

This measure represents the difference between the probability of the occurrence CE when the event k occurs and the probability the same when the event k does not occur. According to this, Equation (1) can be also written as:

$$I^B(k|t) = P_{CE}(t)\big|_{P_k=1} - P_{CE}(t)\big|_{P_k=0} \tag{2}$$

Therefore, if $I^B(k|t)$ is large, a small change in $P_k(t)$ will lead to a comparatively large change in the probability of the critical event P_{CE} at time (t).

2.3. *Aggregation of Indicators*

The aggregation represents the process of integration of the most relevant indicators of one or more barriers in the risk metric. In general, aggregation is a very hard task for the risk analyst. In this work, reference to the aggregation rules proposed by Scarponi et al. [26] has been made; these are briefly described below.

Assuming that the probability of occurrence of an event, which has to be prevented by means of j barriers, is P_H and i is the number of indicators assigned to the barrier. The process of aggregation can be described by referring to a hierarchy of levels, which is schematized in Figure 6 and comprises:

- Level 1 => Indicators for the barriers ($I_{i,Bj}$), which assume value $v_{i,Bj}$
- Level 2 => Global indicators for the barriers (B_j)
- Level 3 => Barrier function (B_H), which collects the global indicators for all the barriers, preventing the same event (i.e., barriers placed on the same branch of the FTA).

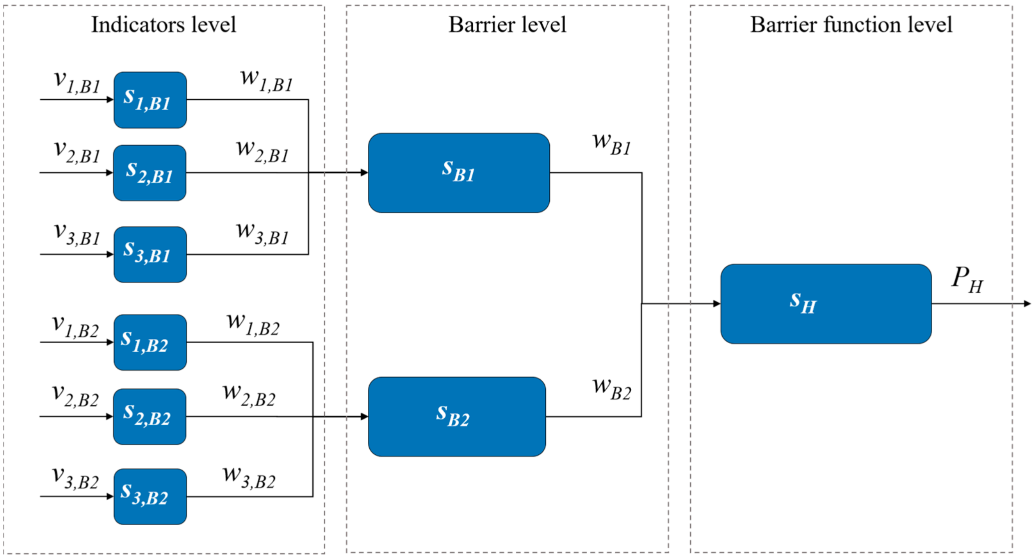


Figure 6. Schematic view of the rules of the aggregation.

As an example, in Figure 6 there are two barriers (j =1, 2), three indicators are associated with each barrier ($I_{i,Bj}$). A barrier could be composed by more elements (sub-barriers), which can be identified by associating j with a letter (a, b, . . .). The steps of aggregation are the following:

1. The value of each indicator $v_{i,Bj}$ must be converted in a score ($s_{i,Bj}$), ranging from 1 to 6; this helps to compare scores of different indicators for the same barrier at the level 1. In converting results in scores, the value 1 represents the most positive score (the barrier works as desired) and 6 the most negative one.
2. A percentage weight ($w_{i,Bj}$) must be assigned to each indicator reflecting its relative importance with respect to the other indicators associated with the same barrier (level 2).
3. The score of each barrier (s_{Bj}) is obtained by means of a weighed summation of the scores of the indicators associated with the same barrier.

$$s_{Bj} = \sum s_{i,Bj} \cdot w_{i,Bj} \tag{3}$$

In case of barriers composed by more elements, an intermediate level must be used to group the scores of these elements for each barrier. The same rules from 1 to 3 are used.

4. All barriers that aims preventing the same event are grouped in an upper level (level 3) to obtain the barrier function (B_H).
5. A percentage weight (w_{Bj}) is assigned to each barrier. This weight reflects its relative importance in relation to the others belonging at the same barrier function.
6. The sum (s_H) of the products of the scores for each barrier and related weight (w_{Bj}) gives the barrier function.

$$s_H = \sum s_{Bj} \cdot w_{Bj} \tag{4}$$

s_H assumes a value from 1 to 6; again 1 expresses the most positive result, whereas 6 is the most negative one.

7. The scores of each barrier function must be translated into a probability of failure (P_H) by means of a direct proportionality in the range of variation of failure probability. Alternatively, other mathematical functions may be also applied by the analyst.

2.4. Data Collection and Review

A systematic data collection of indicators guarantees that the company has updated information to quantify barriers' performance. The updated information allows performing dynamic risk analysis, and also highlights any deviation from set tolerances through an alarm. Such information should be presented in as simple a form as possible. Furthermore, it is very important to review the whole safety management system to make sure that barriers continue to operate as desired and continuously improve the safety. A continuous review of indicators allows verifying their usefulness and efficiency for the prevention of hazard scenarios. This step is important as indicators could not reflect a compliant conduction of the activities due to an alteration in plant design, the improvement of programs, the loss of competence in specific areas, or even the introduction of new risk processes/activities, etc.

3. Case Study

The case study refers is a fictitious oil and gas installation, i.e., a Floating Production Storage and Offloading (FPSO) platform. FPSOs are utilized in newly established offshore oil regions, where there is no pipeline infrastructure in place or in remote locations, where its building is cost-prohibitive. The installation, investigated in this paper, has a diameter of approximately 100 m and features submarine drilled wells, connected to a complete FPSO structure (the name is not mentioned because confidential). The well delivers stabilized crude oil and rich wet gas; the production and processing of hydrocarbons is also made. Oil can also be stored on the platform, until it can be transferred to a tanker to be transported toward its destination.

All platforms include a central shaft, a riser area, a main deck, a process area, a utility area, and a living area. This FPSO is equipped with a platform-crane, which is used to lift heavy objects, such as material supply, equipment, spare parts, and other heavy loads that need to be moved. A typical platform-crane is given in Figure 7; it includes a machinery house, a pedestal, a cabin, a hoisting winch, a luffing winch, a lattice boom, and other elements. Several operations are performed by using the platform-crane and a high rate of accidents is recorded each year. That was of one event per 13.5 installations in 2017, based on a total count of 2108 installations in the continental shelf of the United States [36]. The high incidental rate motivated the choice of this case study.

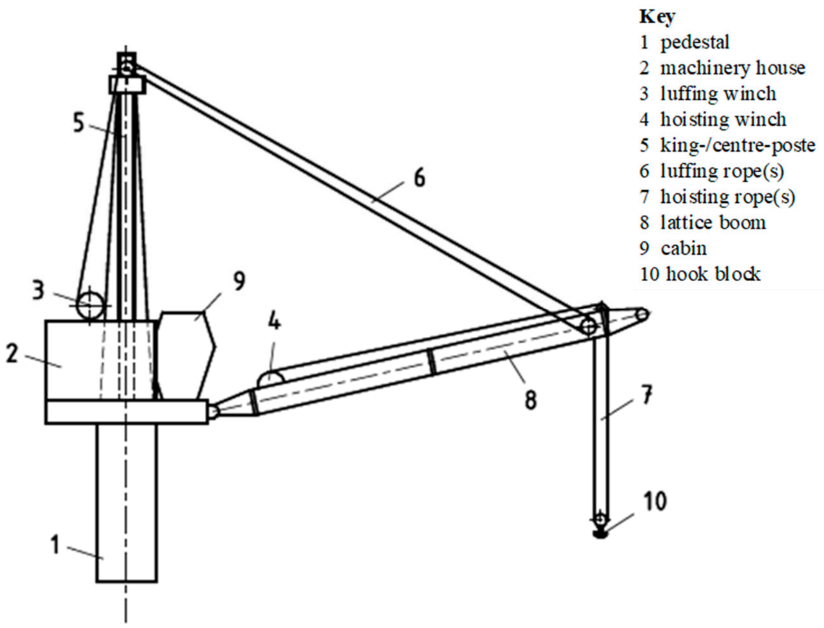


Figure 7. A typical platform crane [2].

Figure 8 gives a schematic view of the crane lifting zones for the case study, where three different areas can be observed: an operational forbidden zone (red area), an operational restricted zone (orange area), and a free lifting zone (grey area). Process accidents start as a leak of hydrocarbons from carrying equipment between the risers in the production area and of crude oil from distribution lines and the blanket gas system on the main deck. Hence, the zones relevant for process accidents are the process area and the main deck area. Hydrocarbon leak hazard is also present in the pump room, the central shaft, and the offloading station area. Concerning crane-operations, there are no lifting above pressurized hydrocarbon equipment. All platform areas, except the dedicated lift zones and laydown areas, are defined as restricted areas and special lifting procedures have to be applied. In the offshore platform, there is a tote tank area (Figure 9), which is a chemical storage area including liquid fuels and various hazardous substances, such as methyl alcohol and monoethylene glycol, that are usually used for hydrate removal [37]. Several load lifting operations could involve this area (≈500 lift/year in a typical platform) and the load could even be a tank containing a dangerous substance. As an example, this area is supplied with methyl alcohol and monoethylene glycol, which are offloaded directly with their container from the supply boat and then lifted to the dedicated area of the deck (tote tank area).

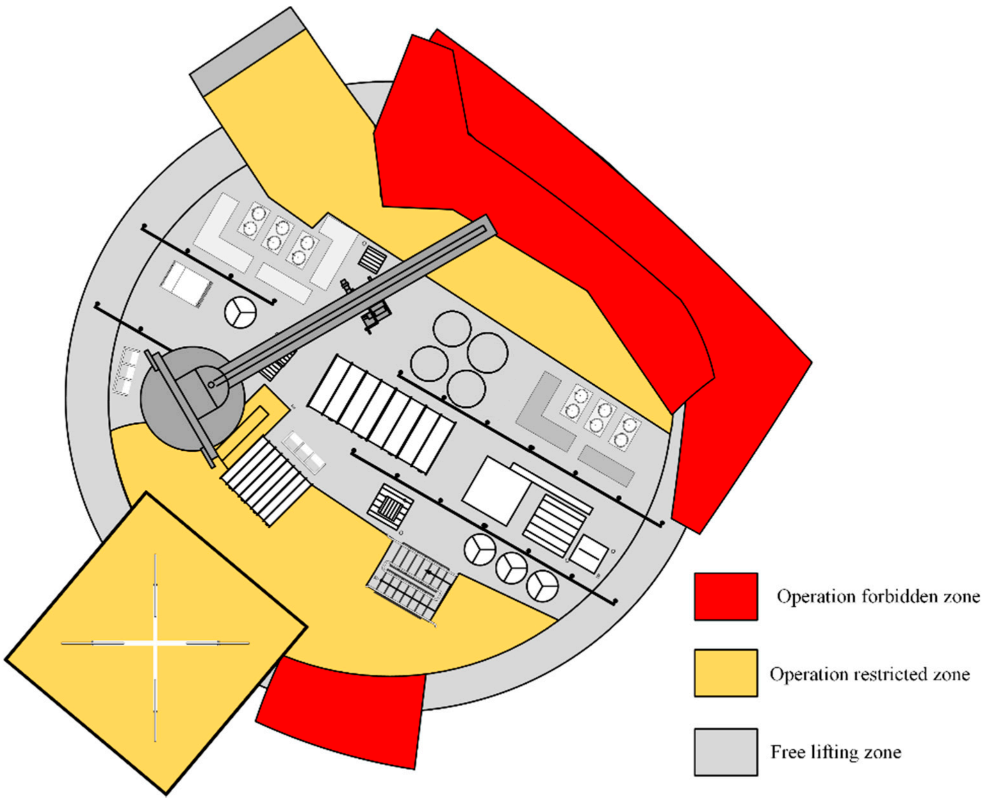


Figure 8. Layout for a crane lifting zones on a generic Floating Production Storage and Offloading (FPSO) platform defined as the case study.

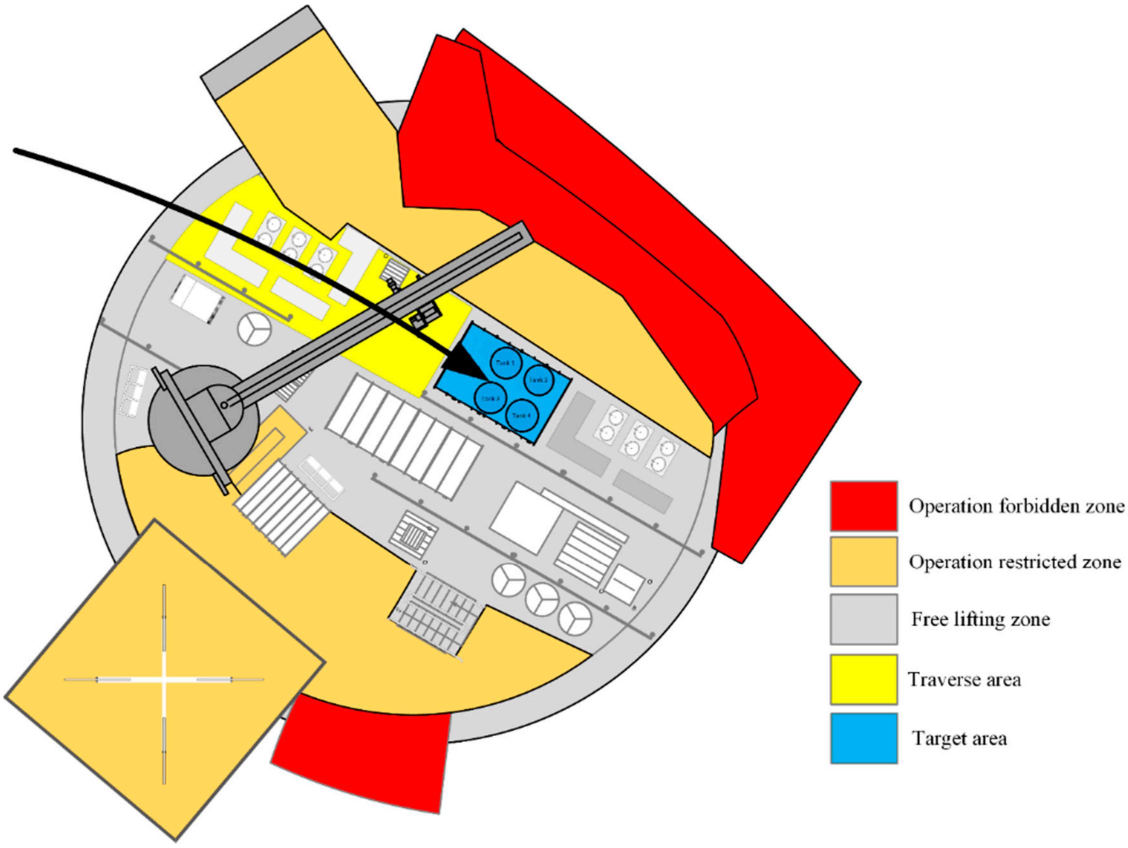


Figure 9. Layout of the tote tank area and the route of the crane boom.

Based on historical data, the dropped object hazard occurs: (i) in the utility area, due to the impact of dropped objects on the roof protecting generators and the multivalve deluge skid, however these scenarios are not expected to cause subsequent fires or explosions (ii) in the process and the spare storage areas, due objects lifted over them, even if the systems are reinforced, depending on the strength of the impact, a release of flammable materials could occur with the following potential occurrence of a fire or an explosion; and (iii) in the tote tank area, again due objects lifted over it or hit with the moving object.

Hypothesis (H1): *Drop of a tank containing methyl alcohol or monoethylene glycol and consequent release of the containment substance due to the hole generated from the impact.*

Hypothesis (H2): *Drop of an object such as a crossbeam or other lifted object on a tank or a pipe in the process area, with the following release of hydrocarbons.*

Hypothesis (H3): *Impact of the lifted object with a tank or a pipe in the process area, with the following release of hydrocarbons.*

Hypothesis (H4): *Impact of the tank containing methyl alcohol or monoethylene glycol (moving object) with a pipeline during the positioning phase inside the tote tank area.*

Hypothesis (H1) has been excluded by the analysis due to the use of protective cage for the tank; hypotheses 2 and 3 are the most frequent case, having a total frequency of $1.41 \cdot 10^{-3}$ event/year; finally, hypothesis 4 has a negligible occurrence. According with these considerations, this investigation has been focused on the hypotheses (H2) and (H3); the equipment under analysis is a tank containing hydrocarbons.

4. Results

The methodology proposed in the Section 2 has been applied to the case study, by focusing on the critical event (CE) associated with the hypotheses 2 and 3, i.e., a breach on the shell of a tank containing hydrocarbons. The CE is due to the drop of an object during its lifting or the impact of the moving object. The bowtie approach allowed identifying its initial causes and related major accidents. By investigating the FTA of Figure 5, the barriers that are in place to prevent or mitigate the LOC have been identified. Figure 10 shows only the branches concerning the crane operability at the FPSO platform. Each cause of the breach on the tank (dropped object and struck by load) has been split up to the identification of their primary initial causes. In the same figure, these events have been also associated with related barriers, described in Table 2. The barrier B2 "Crane operating procedures" has been split in its elements that have been indicated as B2a, B2b, and B2c.

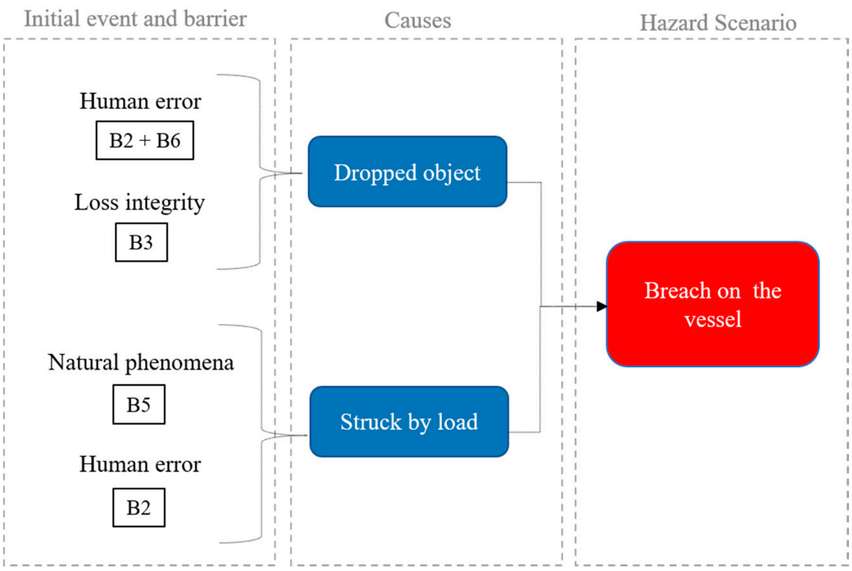


Figure 10. Fault Trees Analysis (FTA) related to the crane operability including the barriers defined for the case study.

Table 2. Barriers.

ID Barrier	Description
B2a	Crane operating procedures (Procedure for the positioning operation)
B2b	Crane operating procedures (Communication rules between the crane-operator and the intermediary (worker) during the positioning phase)
B2c	Crane operating procedures (Procedure for lifting/handling operations)
B3	Inspection and Maintenance procedure
B5	Emergency procedure
B6	VGS

4.1. Risk Indicators for the Crane-Related Operations

A set of reactive and proactive indicators has been defined for each barrier of Table 2, this is given in Table 3. Each lagging indicator controls the achievement of a specific desired scope of the barrier and each leading indicator specifies, in term of success/failure, if the barrier faces to any deviation in performance. With respect to Table 3, the desired outcome is the aim of the barrier and the lagging indicator the parameter measuring the achievement of the desired outcome; the term critical items refers to the elements to be controlled for the success of each barrier and the leading indicators specify the percentage of control that has been reached. According to the HSE approach one lagging indicator and two leading indicators have to be fixed [28].

Table 3. Lagging and leading indicators for the barriers.

Barrier	Desired outcomes	Lagging Indicators	Critical items	Leading Indicators
Crane operating procedures (B2a)	Correct execution of the procedure for the positioning operation	No. of times the lifting/handling/positioning does not proceed as planned	Execution of risk analysis for crane-operation Training coverage: hazardous-properties of products handled, communication systems, load transfer controls and monitoring, and emergency actions	Percentage of activities covered by a preliminary risk assessment - Percentage of staff trained within the reference period.
Crane operating procedures (B2b)	Correct communication between the crane-operator and the intermediary (worker) during the positioning phase	No. of times the communication between the crane-operator and the intermediary (worker) does not support correctly the positioning phase	Execution of risk analysis for crane-operation Training coverage: hazardous-properties of products handled, communication systems, load transfer controls and monitoring, and emergency actions	Percentage of activities covered by a preliminary risk assessment Percentage of staff trained within the reference period.
Crane operating procedures (B2c)	Respect of the threshold limit of velocity of lifting/handling operations	No. of times the velocity of lifting/handling has been exceeded	Execution of risk analysis for crane-operation Training coverage: hazardous-properties of products handled, communication systems, load transfer controls and monitoring, and emergency actions	Percentage of activities covered by a preliminary risk assessment Percentage of staff trained within the reference period.
Inspection and maintenance procedures (B3)	No LOC due to crane failures or to control instrumentation failures. No fires or explosions caused by faulty or damaged electrical elements.	No. of LOCs due to crane failures or to control instrumentation failures.	Failures of critical elements of the crane and identified malfunctions Scope and frequency of the inspection and maintenance	Percentage of critical elements of the crane inspected and repaired Percentage of procedures reviewed and revised within the reference period
Work permit procedures (B4)	High-risk maintenance activities are undertaken in a way that will not cause damage/injury	No. of incidents due to error during maintenance activity.	Clear identification of the scope of activities covered by the permit-to-work Permits specify hazards, risks and control measures Permits are only issued according to proper authorization procedures Duration of the permit Work is conducted as per permit conditions, including demonstration of satisfactory completion of work	Percentage of issued permits with adequate specification of hazards, risks and control measures Percentage of work conducted in accordance with permit conditions

Table 3. *Cont.*

Barrier	Desired outcomes	Lagging Indicators	Critical items	Leading Indicators
Emergency arrangements (B5)	Minimum consequence in case of LOC	No. of elements of the emergency procedures that fail	Emergency plan covers all relevant elements (emergency plan, alarms, shutdown/isolation procedures, firefighting, communication, evacuation)	Percentage of elements that have not failed Percentage of staff/contractors who take correctly emergency actions
Visual guidance System (B6)	Full view of the working area and warning in case of approaching collision No impact between crane/load handled and trespasser in the working area	No. collision between load/crane and obstacles	Device correctly shows the workspace and included elements Alarm activated at the desired set points Knowledge of tasks and relevant experience about substances, work processes, hazards, and emergency actions	Percentage of correct indications Percentage of warning at the set point

4.2. Frequency Assessment

Figure 11 is the core of the bowtie. On the left side of the scheme, only the causes concerning the crane operability have been reported; on the right one, an ETA should be developed, from which the breach on the vessel evolves and gives a loss of containment, whose escalation identifies major accidents. The focus of this study was only the FTA. The initial frequencies, used to estimate the frequency of the LOC, are shown in the figure. Such values have been taken from the report containing the Quantitative Risk Analysis (QRA) of the FPSO. Figure 12 shows two detailed fault trees associated with the crane operability that, respectively, refer to the conduction of lifting operations without any technological device, by means of the support of an intermediary (worker) in navigating the load (Figure 12a), and with the inclusion of the VGS as a further barrier (Figure 12b). The LOC could be originated by a dropped load from the crane on the tank or because it is struck by the load. The event dropped object might be due to the loss of integrity of a part of the crane, which is associated with the failure of the barrier B3, i.e., inspections and maintenance, or to a wrong execution of the positioning, linked to the failure one of two barriers B2a and B2b, i.e., an error in following the positioning procedure or a communication error between the crane-operator and the intermediary (worker) in the case of limited visibility of the working area. The event struck by load could be caused by a high amplitude of vibration for strong winds, associated with the failure of the barrier B5, i.e., emergency procedure, or to a human error due a high velocity execution of the lifting, connected with the failure of barrier B2c, i.e., error in executing the lifting procedure. In Figure 12b, the failure of B2b has been mitigated by using the VGS (B6).

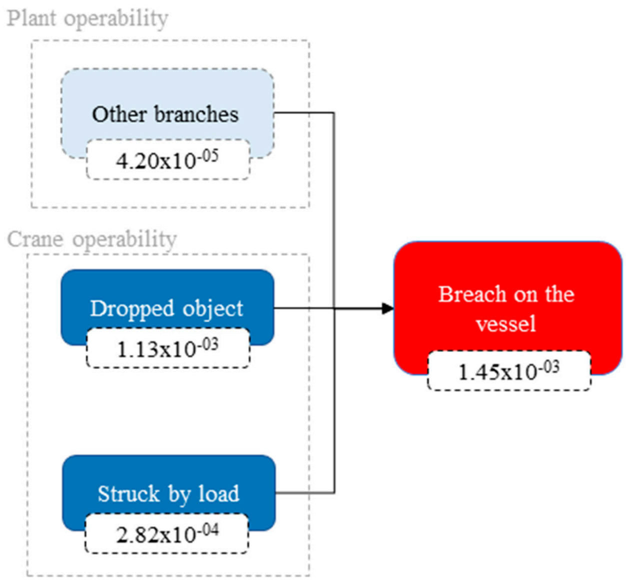
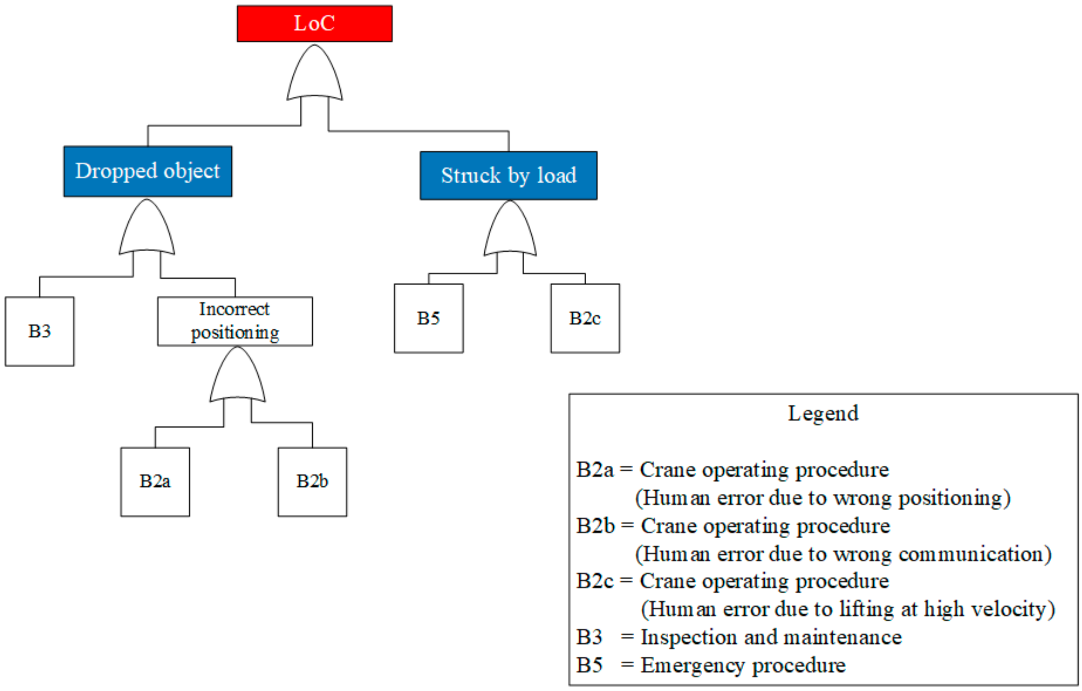
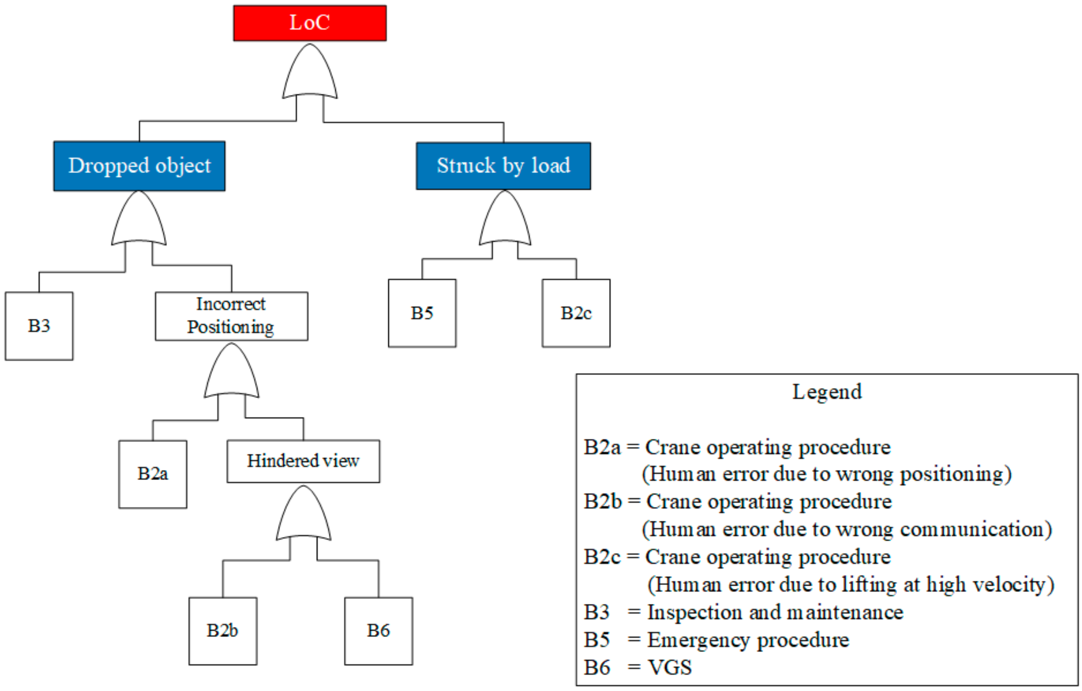


Figure 11. Frequency of main causes originating the breach due to the crane activity.



(**a**)



(**b**)

Figure 12. Detailed fault tree analysis accounting for the crane operability at the FPSO platform: (**a**) conduction of lifting operations without any technological device, and (**b**) inclusion of the Visual Guidance System (VGS).

The traditional Boolean algebra has been used to derive the Minimal Cut Sets (MCSs) for the fault trees of Figure 12, i.e., the sets of basic events, whose simultaneous occurrence ensures that the breach of the shell of the tank, have been determined. Equations (5) and (6) give, respectively, the

MCSs and the probability of the LOC for the first FTA, while equations (7) and (8) give the same for the second one:

$$LOC_{without\ tech.\ device} = B2a + B2b + B2c + B3 + B5 \tag{5}$$

$$P_{LOC\ without\ tech.\ device} = P_{B2a} + P_{B2b} + P_{B2c} + P_{B3} + P_{B5} \tag{6}$$

$$LOC_{with\ VGS} = B2a + B2b + B2c + B3 + B5 + B6 \tag{7}$$

$$P_{LOC\ with\ VGS} = P_{B2a} + P_{B2b} + P_{B2c} + P_{B3} + P_{B5} + P_{B6} \tag{8}$$

After the identification of the MCSs, a sensitivity analysis has been made to determine the importance of each barrier by means of the use of Equation (2). Given the use only of gate OR, all barriers have the same importance (I^B = 1). The Birnbaum's importance measure gives the maximum variation of the LOC probability with respect to each variable that, in turn, is the probability of failure of each barrier. Obviously, these variable range between their minimum and maximum value, i.e., between 0, corresponding to the certain success of the barrier, and 1, representing its certain failure. Table 4 gives the probabilities of failure of each barrier: the probability of failure in the load positioning due to a limited visibility of working area (P_{B2a}) has been found in Milazzo et al. [1]; the probability of structural failure of the crane (P_{B3}) has been taken from Halme and Aikala [38]; the probability for struck by load due to strong winds (P_{B5}) has been derived from data found in the QRA report of the FPSO; finally, the probability of failure of the VGS (P_{B6}) is a value fixed during tests made by the developers of the device [7]. Finally, the probability of failure of the procedure of communication with the operator P_{B2b} and the probability of failure of the procedure of lifting P_{B2c} have been derived by using both the frequencies of dropped object and struck by load, used in the QRA report of the FPSO and the FTA of Figure 12a.

Table 4. Probability of failure of the barriers.

ID Barrier	P_{Bj} [*event/year*]
B2a	0.54
B2b	0.02
B2c	0.190
B3	0.236
B5	0.10
B6	0.020

4.3. Aggregation of Indicators and Frequency Updating

The process of aggregation has been developed according to the three levels described in Section 2.3; it has been applied to both the events leading to the CE, i.e., event 1 = dropped object or *DROP* (Figure 13) and event 2 = struck by load or *STRUCK* (Figure 14). Two barriers function have been defined, respectively, B_{H1} for *DROP* and B_{H2} for *STRUCK*. In Figure 13, B2 includes two elements that are B2a and B2b, while in Figure 14, B2 refers to B2c.

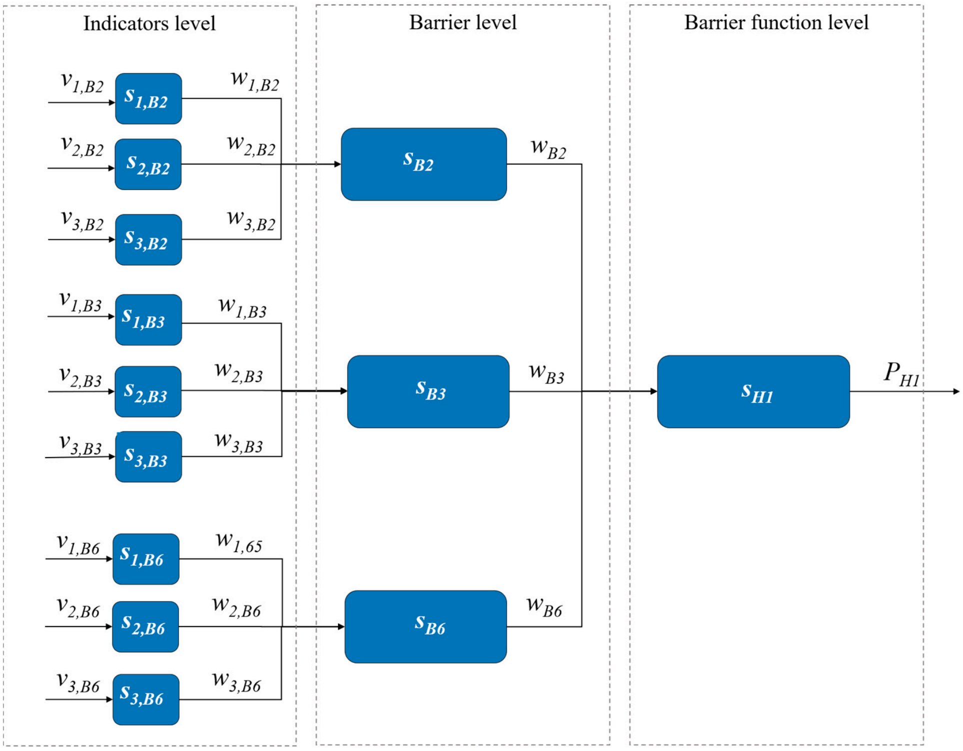


Figure 13. Aggregation of indicator for the branch developing the event *DROP*.

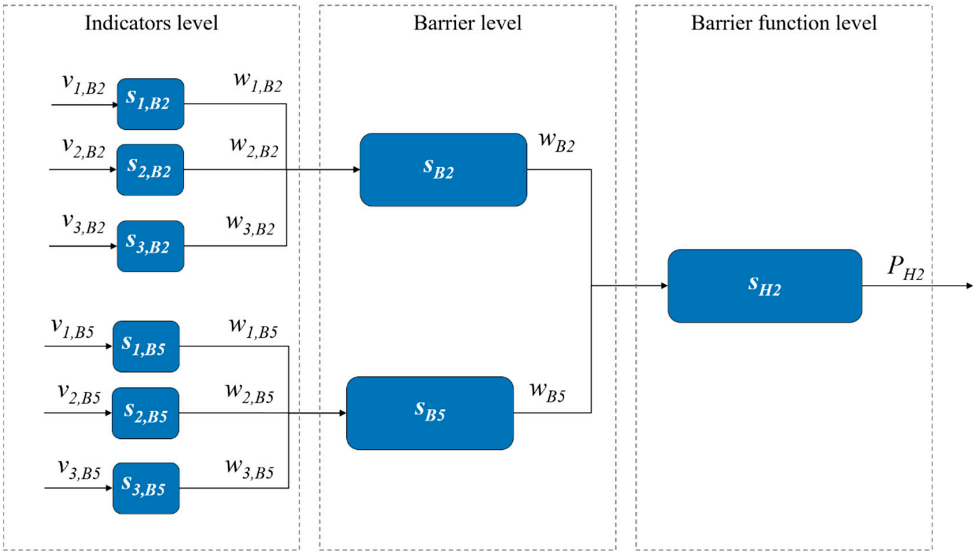


Figure 14. Aggregation of indicator for the branch developing the event *STRUCK*.

At the first level of the aggregation process, the values ($s_{i,Bj}$) of the indicators of each barrier ($I_{i,BJ}$), identified in Section 4.1 have been properly translated in scores (ranging 1 ÷ 6) and, then, weighted to reflect their relative importance with respect to the other indicators associated with the same barrier. The scores have been assigned by using the criteria of Table 5, which in turn have been derived from the analysis of the trend of accidents and near-misses in crane-related operations for Norwegian offshores [39]. The weights have been allocated to each indicator after a discussion with expert risk analysts. Scores ($s_{i,Bj}$) and weight percentages ($w_{i,Bj}$) of each indicator for the case study are shown in Table 6.

Table 5. Criteria to assign scores.

Indicator	Score 1	Score 2	Score 3	Score 4	Score 5	Score 6
No. of times the lifting/handling/ positioning does not proceed as planned ($I_{B2a,1}$)	0 ev./year	5 ev./year	10 ev./year	20 ev./year	30 ev./year	50 ev./year
Percentage of activities covered by a preliminary risk assessment ($I_{B2a,2}$)	100%	80%	60%	40%	20	0%
Percentage of staff trained within the reference period ($I_{B2a,3}$)	100%	80%	60%	40%	20	0%
No. of times the communication between the crane-operator and the intermediary (worker) does not support correctly the positioning phase ($I_{B2b,1}$)	0 ev./year	5 ev./year	10 ev./year	20 ev./year	30 ev./year	50 ev./year
Percentage of activities covered by a preliminary risk assessment ($I_{B2b,2}$)	100%	80%	60%	40%	20	0%
Percentage of staff trained within the reference period ($I_{B2b,3}$)	100%	80%	60%	40%	20	0%
No. of times the threshold limit of velocity of lifting/handling operations is not respected ($I_{B2c,1}$)	0 ev./year	5 ev./year	10 ev./year	20 ev./year	30 ev./year	50 ev./year
Percentage of activities covered by a preliminary risk assessment ($I_{B2c,2}$)	100%	80%	60%	40%	20	0%
Percentage of staff trained within the reference period ($I_{B2c,3}$)	100%	80%	60%	40%	20	0%
No. of LOCs due to crane failures or to control instrumentation failures ($I_{B3,1}$)	0 ev./year	10^{-2} ev./year	$5{\cdot}10^{-2}$ ev./year	10^{-1} ev./year	0.5 ev./year	1 ev./year
Percentage of critical elements of the crane inspected and repaired ($I_{B3,2}$)	100%	80%	60%	40%	20	0%
Percentage of procedures reviewed and revised within the reference period ($I_{B3,3}$)	100%	80%	60%	40%	20	0%
No. of elements of the emergency procedures that fail ($I_{B5,1}$)	0	1	2	3	4	5
Percentage of elements that have not failed ($I_{B5,2}$)	100%	80%	60%	40%	20	0%
Percentage of staff/contractors who take correctly emergency actions ($I_{B5,3}$)	100%	80%	60%	40%	20	0%
No. collision between load/crane and obstacles ($I_{B6,1}$)	0	1	2	3	4	5
Percentage of correct indications ($I_{B6,2}$)	100%	80%	60%	40%	20	0%
Percentage of warning at the set point ($I_{B6,3}$)	100%	80%	60%	40%	20	0%

Table 6. Scores and weight percentages of indicators for the barrier.

ID Barrier	Indicator	Score Indicator $s_{i,Bj}$	Weight [%] $w_{i,Bj}$	Score Global Indicator s_{Bj}
B2a	No. of times the lifting/handling/ positioning does not proceed as planned	2	70%	1.85
	Percentage of activities covered by a preliminary risk assessment	1	15%	
	Percentage of staff trained within the reference period.	2	15%	
B2b	No. of times the communication between the crane-operator and the intermediary (worker) does not correctly support the positioning phase	2	70%	2
	Percentage of activities covered by a preliminary risk assessment	3	15%	
	Percentage of staff trained within the reference period.	1	15%	
B2c	No. of times the threshold limit of velocity of lifting/handling operations is not respected	1	70%	1
	Percentage of activities covered by a preliminary risk assessment	1	15%	
	Percentage of staff trained within the reference period.	1	15%	
B3	No. of LOCs due to crane failures or to control instrumentation failures.	3	50%	2.5
	Percentage of critical elements of the crane inspected and repaired	2	20%	
	Percentage of procedures reviewed and revised within the reference period	2	30%	
B5	No. of elements of the emergency procedures that fail	3	50%	3
	Percentage of elements that have not failed	3	20%	
	Percentage of staff/contractors who take correctly emergency actions	3	30%	
B6	No. collision between load/crane and obstacles	1	20%	1
	Percentage of correct indications	1	20%	
	Percentage of warning at the set point	1	60%	

At the second level, each item of the sets of barriers, associated with the event 1 and event 2 (identified by the branches of the tree), has been assigned by a proper score (s_{Bj}), which is given by the weighed summation of the values of the indicators associated with each barrier, i.e.,$s_{Bj} = \sum (s_{i,Bj} \cdot w_{i,Bj})$ and represents the global indicator for the barrier B_j. Table 7 gives the scores and weight percentages for the barriers; the weight for the barrier is derived by the sensitivity analysis. Finally, at the third level, all barriers that aims preventing the same event have been grouped in an upper level to obtain the barrier function (B_H); this has been made by calculating the weighted summation of the score for the global indicator of the barrier, i.e., $s_H = \sum (s_{Bj} \cdot w_{Bj})$.

Table 7. Scores and weight percentages of global indicators for the barriers.

Barrier	Barrier Function 1 (B_{H1}) S_{H1}		Barrier Function 2 (B_{H2}) S_{H2}	
	Score s_{Bj}	Weight [%] w_{Bj}	Score s_{Bj}	Weight [%] w_{Bj}
Crane operating procedures (B2)	1.92	50%	1	50%
Inspection and maintenance procedures (B3)	2.5	25%	Not included	
Emergency procedures (B5)	Not included		3	50%
VGS (B6)	1	25%	Not included	
Barrier Function results	1.84		2.00	

By using the results obtained at the third level of the aggregation method, i.e., the scores for the barrier functions, the frequency of the event 1 and event 2 has been modified by means of a Risk Metric Reduction Factor (RMRF). The RMRF has been properly defined by assuming a directly proportional relationship between it and the score of the barrier function, which is shown in Figure 15 on the left axis, whereas on the right one there is the efficiency of barriers in reducing the LOC. It has been assumed that RMRF is equal to 0 when the score for the barrier function is 1, that is the maximum theoretical reduction of risk corresponding to the 100% of efficiency of the barriers; on the contrary, the value of 1 has been set when the score is 6, in this case that is the minimum theoretical reduction of risk corresponding to the 0% of efficiency of the barriers.

Given that the S_{H1} is 1.84 (dropped object) and S_{H2} is 2 (struck by load), the RMRF has, respectively, the values 0.17 (83% of efficiency for the barriers on the first branch) and 0.20 (80% of efficiency for the barriers on the second branch). Table 8 gives the results of frequency updating for the critical event, calculated by means of the following relation:

$$F_{updated} = RMRF \cdot F_{initial} \tag{9}$$

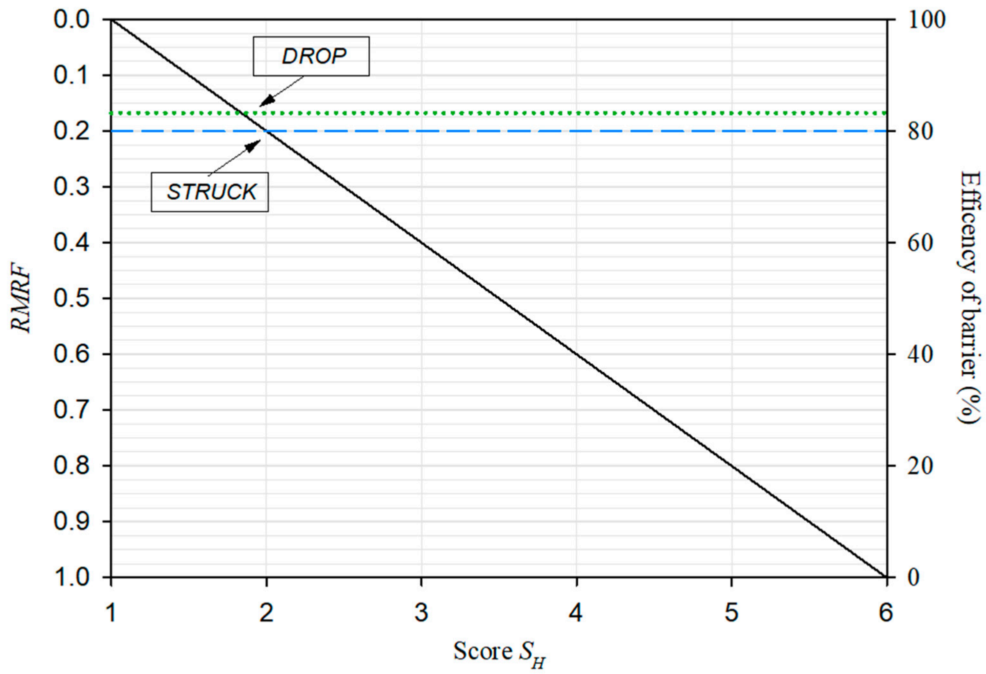


Figure 15. Risk Metric Reduction Factor (RMRF) and efficiency barriers vs. score for the barrier function.

Table 8. Frequency results.

Parameters	$F_{Initial}$ [event/year]	$F_{Updated}$ [event/year]
F_{Drop}	$1.13 \cdot 10^{-03}$	$1.89 \cdot 10^{-04}$
F_{Struck}	$2.82 \cdot 10^{-04}$	$5.64 \cdot 10^{-05}$
F_{LOC}	$1.41 \cdot 10^{-03}$	$2.45 \cdot 10^{-04}$

It can be observed that the initial frequency of the loss of containment (critical event), as well as that of its initial causes has been considerably reduced by the introduction of a new safety barrier (B6). The reduction reaches about the 80% for events associated with the drop of objects (Figure 16). The new barrier is in fact an innovative safety device that allows preventing falls of lifted objects, thanks to an increase in the visibility of the work area provided to the crane operator. The use of VGS and the acquisition of data in real time also offers the advantage of a periodic updating of the frequency, i.e., each time a crane operation is performed.

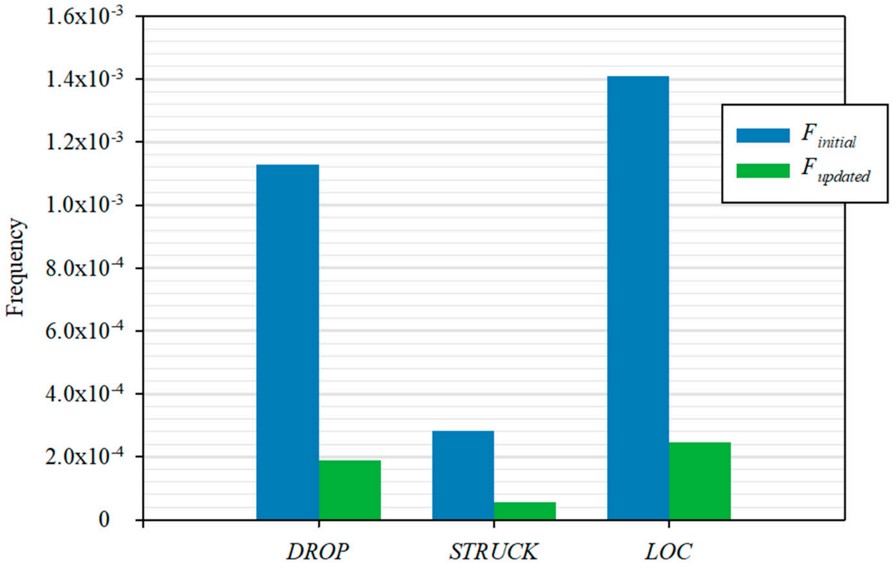


Figure 16. Frequency reduction.

Figure 16. Frequency reduction.

5. Conclusions

Classical quantitative risk analysis provides a static risk picture of major hazard installations, whereas an approach evaluating risk, based on constant information updating, allows taking advantage of early warning indicators to lower the probability of occurrence of undesired events. Moreover, the continuous updating of information supports decision-making and risk communication. These concepts have been already acquired in chemical process industry, but they need to be adapted in contexts where activities, other than chemical context, are performed. This is case of the use of equipment for lifting/handling load.

In this work, a methodology has been proposed for the integration of dynamic features into the risk assessment procedure by taking into account the interaction between the plant activity and crane operations. The method has been based on the approach proposed by Scarponi et al. [26]. Firstly, it consisted of the definition of a set of risk indicators for the load lifting and handling in a typical oil and gas industry, by adapting the HSE approach. In this way, by following the principle for which few significant indicators allow a properly focus on actual criticalities, the most relevant indicators for the activity under analysis have been selected and aggregated by means a proper risk model. Then, a dynamic risk assessment has been performed by means of the bowtie method, which allowed estimating frequencies of the events and their updating, by including the effect of safety barriers. Furthermore, a new safety barrier (VGS) preventing crane accidents due to a hindered view, has been also integrated in the assessment. It allowed a strong reduction of the risk level, as well as a plausible updating of probability by means of a real time data acquisition during crane operations.

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Nomenclature

Symbol	Description
I^B	Birnbaum's measure
k	The event of failure of the barrier system
t	Time
P_{CE}	Probability of the *Critical Event*
P_k	Probability of an input event k
$I_{i,Bj}$	Indicators for the barriers
$v_{i,Bj}$	Value of indicators for the barriers
j	Number of barriers
P_H	Probability of occurrence of an event
i	Number of indicators assigned to each barrier
$I_{i,Bj}$	Indicators for the barriers
B_j	Global indicators of the barriers
B_H	Barrier function
$v_{i,Bj}$	Value of the indicator $I_{i,Bj}$
$s_{i,Bj}$	Score of the indicator $I_{i,Bj}$
$w_{i,Bj}$	Percentage weight of the indicator $I_{i,Bj}$
s_{Bj}	score of the barrier system
w_{Bj}	percentage weight of the barrier system
S_H	scores for the barrier function
$LOC_{without\ tech.device}$	Loss of containment due to crane operation without any technological device
$P_{LOC\ without\ tech.device}$	Probability of $\mathrm{LOC}_{\mathrm{without\ tech.device}}$
B2a	Barrier system - Crane operating procedures (Human error due to wrong positioning)
B2b	Barrier system - Crane operating procedures (Human error due to wrong communication)
B2c	Barrier system - Crane operating procedures (Human error due to lifting at high velocity)
B3	Barrier system-Inspection and maintenance procedures
B5	Barrier system-Emergency procedures
B6	Barrier system-VGS
$LOC_{with\ VGS}$	Loss of containment due to crane operation with the VGS
$P_{LOC\ with\ VGS}$	Probability of $LOC_{with\ VGS}$
P_{B2a}	Probability of *B2a*
P_{B2b}	Probability of *B2b*
P_{B2c}	Probability of *B2c*
P_{B3}	Probability of *B3*
P_{B5}	Probability of *B5*
P_{B6}	Probability of *B6*
P_{Bj}	Probability of barrier j
S_{H1}	Score of the barrier function 1 (branch *dropped object*)
S_{H2}	Score of the barrier function 2 (branch *struck by load*)
$F_{updated}$	Frequency updated
RMRF	Risk Metric Reduction Factor
$F_{initial}$	Initial frequency
F_{LOC}	Frequency of the LOC
F_{Drop}	Frequency of the DROP
F_{Struck}	Frequency of the STRUCK

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Article

Deep Structure, Tectonics and Petroleum Potential of the Western Sector of the Russian Arctic

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Abstract: The evolutionary-genetic method, whereby modern sedimentary basins are interpreted as end-products of a long geological evolution of a system of conjugate palaeo-basins, enables the assessment of the petroleum potential of the Western sector of the Russian Arctic. Modern basins in this region contain relics of palaeo-basins of a certain tectonotype formed in varying geodynamic regimes. Petroleum potential estimates of the Western Arctic vary broadly—from 34.7 to more than 100 billion tons of oil equivalent with the share of liquid hydrocarbons from 5.3 to 13.4 billion tons of oil equivalent. At each stage of the development of palaeo-basins, favourable geological, geochemical and thermobaric conditions have emerged and determined the processes of oil and gas formation, migration, accumulation, and subsequent redistribution between different complexes. The most recent stage of basin formation is of crucial importance for the modern distribution of hydrocarbon accumulations. The primary evolutionary-genetic sequence associated with the oil and gas formation regime of a certain type is crucial for the assessment of petroleum potential. Tectonic schemes of individual crustal layers of the Western sector of the Russian Arctic have been compiled based on the interpretation of several seismic data sets. These schemes are accompanied by cross-sections of the Earth's crust alongside reference geophysical profiles (geo-traverses). A tectonic scheme of the consolidated basement shows the location and nature of tectonic boundaries of cratons and platform plates with Grenvillian basement as well as Baikalian, Caledonian, Hercynian, and Early Cimmerian fold areas. Four groups of sedimentary basins are distinguished on the tectonic scheme of the platform cover according to the age of its formation: (1) Riphean-Mesozoic on the Early Precambrian basement; (2) Paleozoic-Cenozoic on the Baikalian and Grenvillian basements; (3) Late Paleozoic-Cenozoic on the Caledonian basement; (4) Mesozoic-Cenozoic, overlying a consolidated basement of different ages. Fragments of reference sections along geo-traverses illustrate features of the deep structure of the main geo-structures of the Arctic shelf and continental regions of polar Russia.

Keywords: tectonic zoning; deep structure of the Earth's crust; Western Russian Arctic; reference geological and geophysical sections (geo-traverses); petroleum potential of the Western Russian Arctic; resource base of the Arctic shelf

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1. Introduction

At the present stage of regional oil and gas exploration in the Arctic, much attention is given to studies of the deep structure of sedimentary basins in conjunction with studies of the consolidated basement underlying them. Such an approach allows the assessment of the age interval and geodynamic settings of the platform cover formation, the morphology of these structures, and the nature of the tectonic dislocations.

At the present level of regional geological and geophysical studies of the Russian Federation and adjacent continental shelf development of new methodological approaches to the geotectonic modeling of structural and compositional inhomogeneities of the Earth's crust, their geodynamic and evolutionary interpretation, and the implementation of regional forecast-mineragenic estimates for various types of ore and nonmetallic minerals, are of particular relevance.

The lithosphere-scale 3-D structural model of the Barents Sea and Kara Sea region of Klitzke et al. [1,2] was the first attempt to combine information about sediments, crystalline crust and lithospheric mantle.

This model refines the four main mega-sequence boundaries: the bottom of the upper crystalline crust, the Moho, and the calculated lithosphere–asthenosphere (LAB) boundary.

The Northern (1) and Southern (2) Kara Sea, the Eastern (3) and Western (4) Barents Sea, and the oceanic domain comprising the Norwegian–Greenland Sea and the Eurasia Basin (5) are the five main offshore areas. The western Barents Sea is underlain by a thin (~80 km) lithosphere. It was formed through multiple Phanerozoic rifting phases and/or the opening of the Atlantic starting from Paleocene/Eocene times onwards.

The most important results of the development of the structural model [3] for the assessment of petroleum potential relate to the South-West Barents Sea and show a classical rift system with major extensional faults.

More recent research resulted in the compilation of a tectonic map of the Arctic [4] that shows the age and main structural features of coastal and oceanic sedimentary basins of the Barents, Kara, Laptev, East Siberian, and Chukotka Seas [5]. The basement structure of these basins and Arctic islands is also discussed.

The database of regional investigations of the deep structure of the crust, tectonics, and geodynamics of sedimentary basins and fold areas includes refraction and reflection (CDP) seismic data, deep seismic sounding (DSS) data, magnetotellurics (MT), audio magnetotellurics (AMT) sections, digital potential fields, and remote sensing data. Geological mapping results and geological and geophysical studies of wells were also used to inform our interpretations. These were collected in the framework of government programs of reference regional geophysical profiles (geo-traverses), regional-scale geological mapping, and regional geological studies of main geo-economical regions (Figure 1).

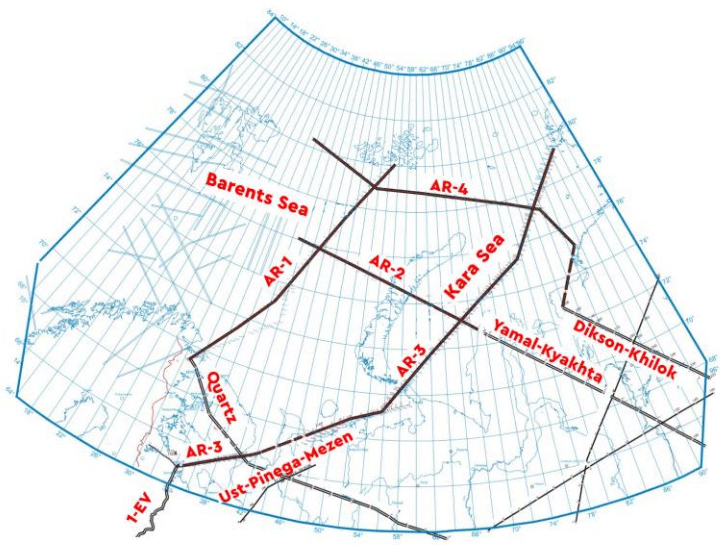

Figure 1. Location of deep seismic profiles in the study area (EV-European, AR-Arctic).

Within the framework of investigations of the Russian sector of the Eurasian Arctic, we have carried out geotectonic interpretation of the regional seismic profiles of the Barents-Kara Sea region: "AR-1", "AR-2", "AR-3" and "AR-4" (Figure 1) [6]. These data were acquired by the State Enterprise "Sevmorgeo". We have also interpreted multiple geophysical datasets collected along regional deep seismic sounding (DSS) profiles "Quartz", "Yamal-Kyakhta", "Dikson-Khilok", as well as the reflection seismic data acquired by "Spetsgeofizika" along "1-EV" and "Ust-Pinega-Mezen" profiles. The regional geoelectric, gravity and magnetic data were utilized to inform our interpretations [7].

2. Research Methodology

The process of our investigations included several stages, from the processing of geophysical data to their qualitative and quantitative interpretation followed up by the compilation of geological-structural schemes [7].

We model the deep structure of the Earth's crust underlain by a layer of the lithospheric mantle [7] based on geological and geophysical data. In our approach, we distinguish the volcanogenic-sedimentary layer and consolidated crust. The crust is divided into upper crustal (granite-metamorphic), middle crustal, and lower crustal layers. In some cases, the last two layers are combined into a single lower crustal layer.

In our research, we have encountered two serious methodological problems:

1. Large differences in the morphology of platform cover structures and of consolidated basement and information overload of maps of deep structure which, in essence, are geotectonic, and which simultaneously reflect the structure of both sedimentary cover and basement. This cartographic problem is resolved by compiling layer-by-layer maps of the deep structure and deep sections of the Earth's crust using single ideology and unified legend.
2. An extensive time interval of the formation and subsequent evolution of platform cover and consolidated basement structures of the Eurasian Arctic. To solve this problem, a geotectonic approach is applied to the process of the modeling of structural and compositional inhomogeneity of the Earth's crust.

The key construction tool in this methodology is a zonal-block model of the lithosphere [8] based on the results of specialized processing and comprehensive interpretation of seismic (DSS and CDP), gravimetric, magnetic, geoelectric, and geothermal data. It reflects blocks and inter-block zones separating them. Blocks are characterized by regionally stable areas of geophysical fields and derived parameters; inter-block zones—by gradient zones, or zones of drastic change in the potential field pattern and infrastructure of parameters calculated from potential field data. In the resulting tectonic model, blocks correspond to palaeo-plates and microplates of continental lithosphere, inter-block zones—to deep tectonic sutures that have resulted from extension (rifts), compression (sutures of collision orogens), or strike-slip movements [7].

In our geotectonic modelling of basement structures, we relied on one of the most generally accepted principles of tectonic zoning based on the age of the final folding. According to Khain [9], time boundaries of geotectonic cycles reflect the periodic consolidation of continental lithosphere into a single supercontinent, or the partial closure of an ocean due to periodic collisions of volcanic island arcs with continents (Bertrand cycles).

One of the assessment methods of the oil and gas potential [10] of sedimentary basins is evolutionary-genetic, based on the concept that each complex and heterogeneous modern basin is a system of laterally and vertically conjugated palaeo-basins of a certain tectonotype, or relicts of such palaeo-basins [7,11]. Each sedimentary basin has formed in certain geodynamic regimes and went through a long geological evolution. At certain stages of basin development, favorable geological, geochemical, and thermobaric conditions have emerged that determine the processes of oil and gas formation and their redistribution between various complexes composing these palaeo-basins, as well as processes of partial or complete destruction of oil and gas accumulations. Late stages of basin formation have the greatest impact on the current distribution of hydrocarbon accumulations [9,12,13].

Accordingly, each basin of the primary evolutionary-genetic sequence is characterized by a certain oil and gas formation regime. The concept of oil and gas formation regime, according to Sokolov [14], includes conditions of basin evolution caused by type and movements of the crust, duration of subsidence, rate of sediment accumulation, direction of tectonic movements (vertical or horizontal), their contrast and ratio and basin thermal history.

The petroleum geology regime of a basin defines specific features of source rock and reservoir formation, their relationship in the vertical section, and the timing of oil and gas maturation. It also defines the location of oil and gas palaeo-accumulation zones and their temporal and spatial relations in the process of the spatial and vertical distribution of oil and gas accumulations.

Changes in the geodynamic conditions of basin formation and, consequently, changes in their genetic types lead to the transformation of petroleum geology regimes that ultimately reflect oil and gas potential. As noted by most researchers, oil and gas formation regimes differ in sedimentary basins located within continents, oceans, and transition zones. In turn, within continents, sedimentary basins of platforms and mountain-folded areas have fundamentally different regimes [14–17].

Consequently, it is important to consider the fact that the sedimentary basin is a part of a larger evolving system. The scale of oil and gas accumulation also varies significantly, ranging from high/very high (20–63%) within sedimentary basins of young plates and folded platform basins in marginal parts of cratons, to low (3%) in post-orogenic depressions on Precambrian Midlands, and very low (less than 1%) in orogenic inter-mountain depressions on the epivariscian folded basement.

Alongside with tectonic reconstructions based on regional seismic data interpretation in the western-most part of the Russian Arctic sector, a conventional basin analysis was performed to clarify the assessment of the hydrocarbon potential. The assessment is based on the presence and distribution of source and reservoir rocks, as well as on the impact of tectonic events and major unconformities on hydrocarbon reservoir integrity. The assessment incorporates evaluations of the presence and distribution of oil source and reservoir rocks, and the impact of tectonic events and major unconformities on hydrocarbon reservoir integrity. The study results are based on conventional basin analysis.

We have subdivided sedimentary cover into seismo-stratigraphic complexes, correlated and linked geological and geophysical data onshore and offshore, and compiled a series of structural maps for several reflection horizons (RH) in areas of their identification from the top of the basement (RH VI) to the bottom of Jurassic (RH B). A seismo-geological model was used to refine the tectonic and oil and gas zoning of the North of the Timan-Pechora province, including Pechora Sea.

3. Structure and Composition of the Earth's Crust of the Arctic Sector of Eurasia

The main parameters of the Earth's crust of the region are characterized by tectonic schemes of consolidated basement, platform cover, and deep sections of the crust. The schemes and sections were compiled within a unified legend and can be considered as a 3D geotectonic model of the region.

The most common geodynamic setting of the consolidated crust is a collisional orogen, which is formed in the process of the collision of continents or microcontinents with each other, possibly involving the collision of enzymatic island arcs. They generally correspond to a deformed margin of the submerging plate (fold-thrust belt and foredeep), or a suture zone, marking the position of the former oceanic basin, or the deformed margin of the overlapping plate (Figure 2) [7].

The tectonic zonation of the consolidated basement was carried out according to the time of the principal fold deformations (final folding) (Figure 3) [7].

The Eurasian sector of the Arctic includes the northern part of Europe and Western Asia and the adjacent areas of the Atlantic and Arctic oceans. Divergent plate boundaries are drawn along the Mid-Atlantic spreading ridge and the Gakkel Ridge in the Arctic Ocean.

The most ancient structures of the region are East European and Siberian cratons and Kara and Svalbard platform plates with an ancient Precambrian (Grenvillian) basement. These structures are separated by fold belts: Timan-Pechora, Yenisei and Taimyr Baikalian fold areas; Caledonian structures of Norway, West Spitsbergen, and Altai-Sayan fold areas; Uralian, Central West Siberian, and Taymir-Severnaya Zemlya Hercynian fold areas; Early Cimmerian Paikhoi-Novaya Zemlya fold area [18].

Within the ancient platforms and fold areas, suture zones are mapped. They mark the position of closed riftogenic and oceanic basins and fold-thrust belts formed on the edges of lithospheric plates and microplates.

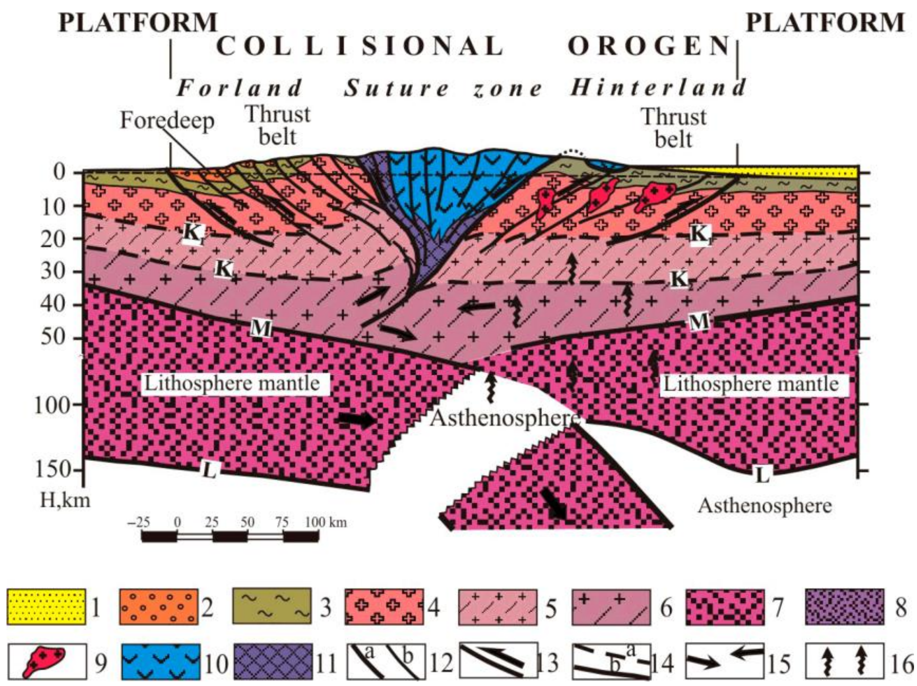

Figure 2. Model of a collisional orogen (Uralian type) [7]. Numbers 1–10 are structural and material units of the lithosphere: 1—weakly deformed sediments of the platform cover; 2—molasses; 3—lithified sediments of the ancient passive margin; 4—granite-gneiss layer; 5—middle crust; 6—lower crust; 7—lithospheric mantle; 8—riftogenic complexes; 9—granitoid plutons; 10—island arc complexes; 11—ophiolites; 12—faults (a-major, b-minor); 13—trends of thrust movements; 14—boundaries of radial stratification of the Earth's crust, including. a—minor (F0—basement of the platform cover, K1—the basement of the upper crustal layer, K2—the basement of the middle crust); b—the basement of the Earth's crust (the boundary of Mohorovichich); 15—trends in relative displacements of segments of the Earth's crust; 16—trends of heat and mass transfer within the orogen.

The suture zones, which separate crustal blocks of various structures, are marked by outcrops of ophiolites and island arc complexes. In the vertical section, such zones have a wedge-shaped morphology and a narrow deep channel. As a result of the collision, the edges of the plates are affected by intense compressional deformations. In the process of collision, the thickness of the brittle upper crust can sharply increase due to the injection of the plastic lower crust and tectonic clustering of the upper crust. This phenomenon of the formation of "mountains roots" is visible in the sections of the Yenisei Khatanga (Figure 4) and Ural fold areas. Typical structures of collisional orogens are tectonic nappes resulting from the abduction of oceanic and island-arc formations on the continental margins (Figure 2). Molasse strata often accumulate within marginal troughs [7].

Our study area contains a broad range of rifts, the ages of which vary from Riphean to Mesozoic and Cenozoic. In all cases, these structures are formed by an association of sedimentary and volcanic rocks. Morphologically, these are structures of fault-bounded grabens.

The tectonic scheme of the platform cover shows features of the upper structural level filled with weakly lithified, weakly deformed platform sediments overlying the consolidated basement (Figure 4).

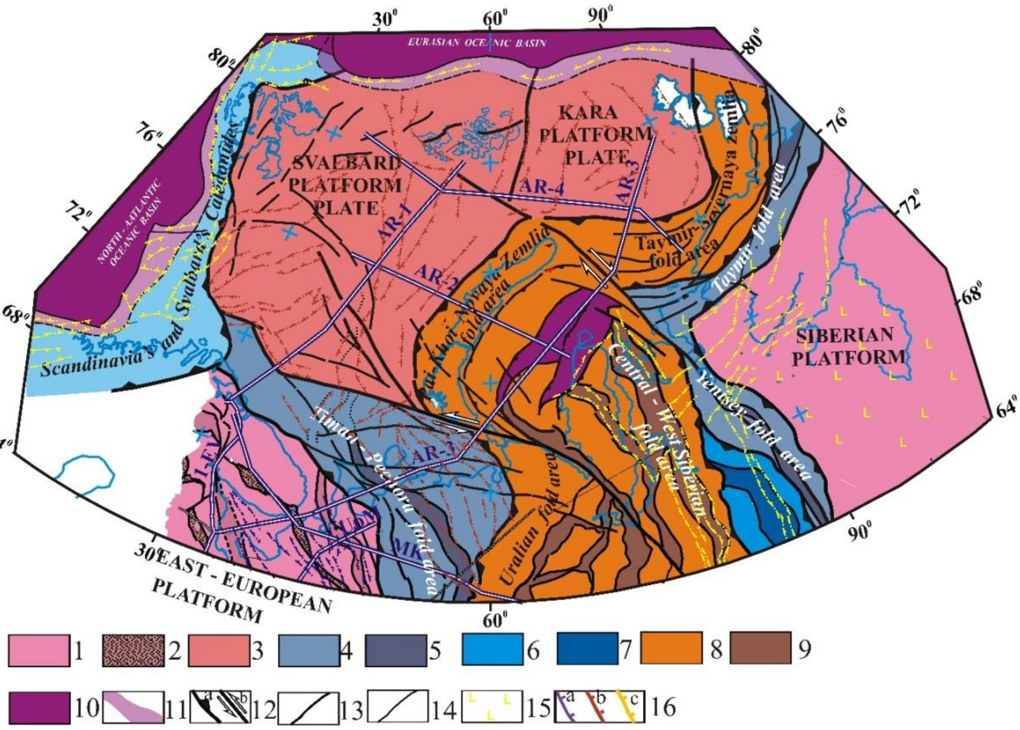

Figure 3. Scheme of tectonic zonation of the consolidated basement of the Eurasian sector of the Arctic. Numbers 1–11 are structural and material units of the Earth's crust: 1–2—ancient platforms (1—blocks, 2—Proterozoic 1 suture zones); 3—blocks of Grenville folding; 4–5 Baikalian fold areas (4—blocks, 5—interblock zones), 6–7—Caledonian fold areas (6—blocks, 7—interblock zones); 8–9 Hercynian and Early Cimmerian (Paikhoi-Novaya Zemlya) fold areas (8 blocks, 9 interblock zones); 10—oceanic basins; 11—continental slope; 12–14—faults (12—major, including thrust faults (a) and strike-slip faults (b), 13—minor, 14—others); 15 — Siberian traps; 16 — riftogenic structures (a—Riphean, b—Paleozoic, c—Mesozoic-Cenozoic).

The largest structural elements in the scheme are sedimentary basins. The color is assigned to the age interval of the cover formation; the intensity of the color depends on its relative thickness. The scheme presents four age intervals of the formation of sedimentary basins: 1—Riphean-Mesozoic sediments of the East European and Siberian cratons; 2—Paleozoic-Cenozoic sediments on the Baikalian (Timan-Pechora fold area) and Grenville (platform plates of Svalbard and Kara) basements; 3—Late Paleozoic-Cenozoic sediments formed on the Caledonides of Scandinavia and West Spitsbergen; 4—Mesozoic-Cenozoic sediments of the West Siberian, South Kara and Yenisei Khatanga sedimentary basins, overlying a consolidated basement of different ages. In the basal part of the West Siberian geo-syneclise, formations of the so-called "intermediate structural level" are distinguished. They are composed of weakly dislocated moderately lithified complexes of the Riphean and Paleozoic age.

The scheme reflects the position of rifts of different ages, which are most often inherited by post-rift troughs, often covering vast territories of platform plates. Anteclises, syneclises, shafts, domes, local uplifts, and structures are presented on the scheme. Special attention is paid to the manifestations of intraplate deformations (Figure 4).

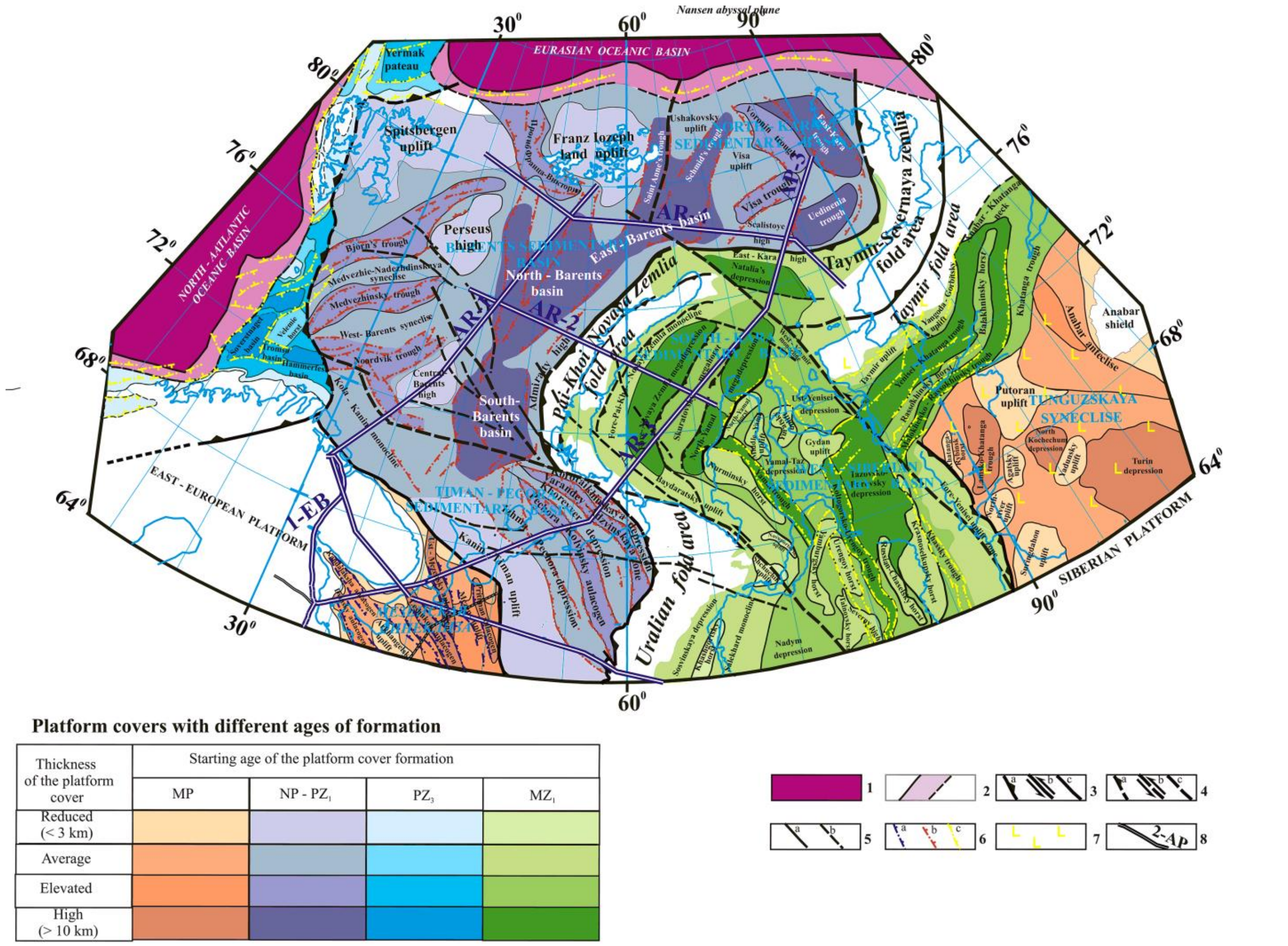

Figure 4. Structural scheme of the platform cover of the Eurasian sector of the Arctic [7]: 1—the oceanic type crust; 2—the continental slope crust; 3—the main faults of the structures of the 1st rank (a—thrusts, b—displacements, c—unknown type); 4—the main faults of the structures of the 2nd grade (a—thrusts, b—displacements, c—unknown type); 5—other fracture defections (a—traced by a number of geophysical data, b—traced by one source); 6—riftogenic structures (a—Riphean, b—Paleozoic, c—Mesozoic); 7—Siberian traps; 8—basic geophysical profiles.

4. Features of the Deep Structure of the Region

East European and Siberian ancient platforms were formed in the process of the Paleoproterozoic accretion of Archean palaeo-plates [9]. Their basement is mainly composed of the old Archean blocks and Paleoproterozoic suture and riftogenic zones. The results of geophysical studies of the suture zones reflect the fold-and-thrust nature of their deformations, often with an inclined deep inter-block channel.

The Svalbard and North Kara platform plates are interpreted as fragments of the Grenville platform, called “Hyperborea” by Shatskiy [19] or “Arctida” by Zonenshain and Natapov [20]. Khain suggested [9] that a platform with a Grenville or even older basement existed in the center of the Arctic in the late Precambrian and Early Paleozoic. Their separation took place at the beginning of the Paleozoic during the disintegration of the Rodinia supercontinent. Fragments of this platform are the Svalbard and Karsky platform plates, the structures of Northern Taimyr, and the Lomonosov, Alpha, and Mendeleev ridges [21]. Within the Arctic Basina, Early Proterozoic crystalline formations are exposed in the east of Spitsbergen and the north of Novaya Zemlya. It is assumed that these outcrops constitute the visible part of the basement, the top parts of which are of Middle Proterozoic age.

The tectonic structure of the consolidated basement of the Eurasian sector of the Arctic is determined by the nature and sequence of accretion of the Svalbard, Bolshezemelskaya, the Baltic, Kara, and Siberia paleo-plates, and numerous microplates.

The Svalbard Platform Plate is interpreted as a Precambrian (Grenvillian) platform with an ancient consolidated basement and Paleozoic-Mesozoic sedimentary cover.

Consolidated basement. Isotope dating of the Grenville (1,150,960 Ma) age of the basement formations was established by Gee et al. [22] in Svalbard. According to seismic survey data on reference and regional profiles, the Grenville basement can be tracked to the southeast from Spitsbergen towards the outer limits of the Kola monocline and the borders of the Timan-Pechora region [7], and to the east—towards the Central block of Novaya Zemlya, and further to the area of the North Kara syneclise. The thickness of the consolidated crust within the Svalbard (Barents) plate varies from 18 to 36–38 km. The most radical reductions in crustal thickness, caused by the processes of its extension, are noted within the East Barents mega-trough. The results of geophysical studies indicate the continental type of crust and significant basification. In the most submerged parts, a positive bend of the Moho boundary is noted, and crust-mantle transition zones up to 10 km thick have been identified [23].

Platform cover. The data on the geological structure and composition of the litho-stratigraphic strata of the cover were obtained in the Novaya Zemlya archipelago, Franz Josef Land, and Spitsbergen. Reference wells in the hydrocarbon fields of the East Barents Basin intersect the full section of the Mesozoic sediments and part of the Upper Paleozoic sediments. According to seismic data, Early Paleozoic deposits deformed to varying degrees are distinguished. They are included in the acoustic basement [24].

The East Barents Sea basin consists of three main basins: South Barents (20 km thick), North Barents (18 km thick), and St. Anna (15 km thick). It is assumed that the main volumes of sedimentation within the basin were formed in the process of the Late Devonian (Frasnian-Famenian) rifting and subsequent post-rift subsidence [12,25–27]. Combined interpretation of CDP seismic data and borehole studies indicates the development of an echeloned system of grabens and half-grabens at the base of the basin, filled with clastic and volcanic deposits with a total thickness of 1.5 to 3.0 km overlying the Early-Middle Paleozoic "acoustic basement". Repeated rifting may have occurred in the Permian-Triassic. Post-rift subsidence led to the formation of up to 1.0–1.5 km deep depression by the end of the Permian. In the Early Triassic, the deep-water basin was rapidly filled with sediments. From the Middle Triassic to the Late Cretaceous marine, shallow-sea and continental environments developed in the axial parts of the East Barents Sea basin [23].

A characteristic section of the eastern flank of this structure is the section along the AR-2 profile. The Barents fold area in this section is represented by the North-Barents depression covering the thinned transition crust of passive continental margin type. Such sections are characterized by the development of all three layers of the classical continental crust with reduced thickness due to rifting. Rifting zones within the depression have a characteristic pattern of "pure shear" deformations with a centric distribution of the faults (Figure 5).

The Kara platform plate is interpreted as a Precambrian (Grenvillian) platform with an ancient consolidated basement and Paleozoic-Mesozoic sedimentary cover. It has been crossed by a large number of regional seismic profiles and two reference geophysical profiles (geo-traverses) AR-3 and AR-4, acquired by state enterprise Sevmorgeo. In combination with data from the geological mapping of the Severnaya Zemlya archipelago, even in the absence of deep drilling wells here, there is an opportunity to carry out deep crustal geological and structural modelling.

The consolidated basement on the islands of Severnaya Zemlya is mainly composed of deformed and metamorphosed shales and sandstones of the Neoproterozoic–Cambrian age [12]. Neoproterozoic granite plutonism is represented by the intrusions of south-eastern October Revolution Island [4,17].

The North Kara sedimentary basin is characterized by a thick (on average more than 5 km) sedimentary cover, increasing in troughs to 15–16 km and reducing to 2–4 km within individual uplifts (e.g., Vize-Ushakova and others). In its southwestern part, the East Barents Basin is identified with a total sediment thickness of up to 14–16 km. To the north, there is the St. Anna's trough, which overlaps the joint of the Svalbard and Kara platform plates and the Schmidt trough. On the eastern and southern flanks of the basin, the East Kara and Uedineniya troughs are mapped. Depressions and troughs are separated by uplifts.

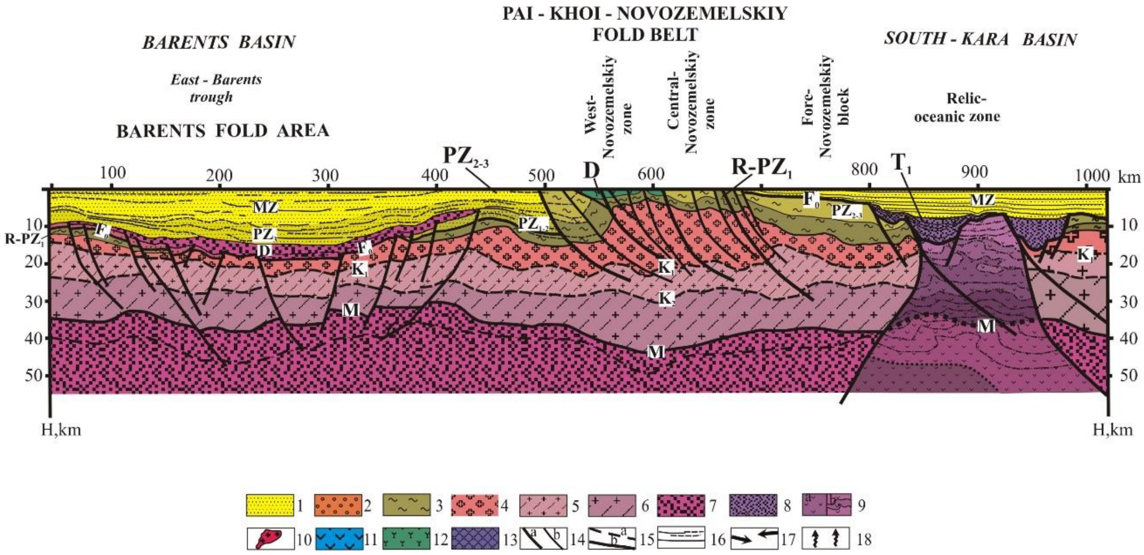

Figure 5. Section of the Earth's crust along the AR-2 geo-traverse. Compiled using materials from State enterprise "Sevmorgeo" [7]. See Figure 2 for legend. Numbers 1–13 are structural and substational units of the lithosphere: 1—weakly deformed sediments of the platform cover; 2—molasses; 3—lithified sediments of the ancient passive margin; 4—granite-gneiss layer; 5—middle crust; 6—lower crust; 7—lithospheric mantle; 8—riftogenic complexes; 9—oceanic type crust, including ifferentiated by the speed of elastic waves; 10—granitoid plutons; 11—island arc complexes; 12—volcanic complexes of active margins; 13—ophiolites; 14—breaking dislocations (a—major, b—minor); 15—boundaries of radial stratification of the Earth's crust, including a—minor (F0—basement of the platform cover, K1—the basement of the upper crust, K2—the basement of the middle crust); b—the basement of the Earth's crust (Mohorovichich boundary); 16—sub-horizontal boundaries and lineaments of the seismic section; 17—trends in mutual displacements of segments of the Earth's crust; 18—trends of heat and mass transfer within the orogen.

Lower Ordovician volcanic-clastic rocks at the base of the sedimentary cover of graben-type depressions overly deformed folded sediments of the acoustic basement. This formation is associated with rift extension [12,25,28]. According to the geological mapping of the Severnaya Zemlya archipelago, Early Paleozoic rifting resulted in the formation of volcanic rocks (andesites, trachytes, and rhyolites) along the N-trending fracture system [4,29].

The composition of the sedimentary cover of the troughs varies according to different authors. According to Daragan-Suscheva et al. [30–32], the section is dominated by the Upper Riphean-Middle Paleozoic rocks that form two structural levels—the Upper Riphean-Cambrian and Ordovician-Devonian. In the modern shelf area, a series of relatively deep-water basins separated by shallower areas existed during the Upper Riphean and Vendian [33]. In these narrow basins, up to 7–9 km of mainly flysch-like terrigenous strata have accumulated. The thickness of the Ordovician-Devonian cover reaches 6 km.

Startseva [34] distinguishes Ordovician-Devonian and Carboniferous-Mesozoic structural levels in the sedimentary cover of the basin. Martirosyan et al. [35] divided the sedimentary cover into two structural levels: (1) the lower one, up to 14–15 km thick, covering the upper Proterozoic and almost the entire (or all) Paleozoic, moderately dislocated and filled with lower terrigenous and upper carbonate complexes; and (2) upper, presumably Mesozoic, represented by terrigenous mainly continental deposits. Their thickness in the east is in hundreds of meters, in the west it increases to 2 km, and in the St. Anna Trough it reaches 6–8 km.

Ordovician to Devonian sediments are deformed by platform-type dislocations [36]. Martirosyan et al. note the widespread development of faults in the Paleozoic part of the sedimentary sequence with an amplitude of 2–3 km [35]. They are mostly interpreted as normal faults.

The deep structure of the Kara plate is illustrated by a fragment of the reference geophysical profile (geo-traverse) AR-4 (Figure 6). In this region, the East Barents Basin filled with deposits from Early Paleozoic to Cenozoic has the largest total thickness of the sedimentary cover (up to 16 km). It has reduced thickness of the Earth's crust (up to 38 km to the background of 40–42 km in adjacent blocks). A sparce grid of deep faults slightly disrupting the continuity of seismic horizons is observed in the lower horizons of the sedimentary cover. Within the Rocky Rise, the thickness of the sedimentary cover is reduced to a few kilometers, possibly due to intraplate compression caused by Hercynian accretion in the adjacent Taimyr-Severozemelskaya fold zone.

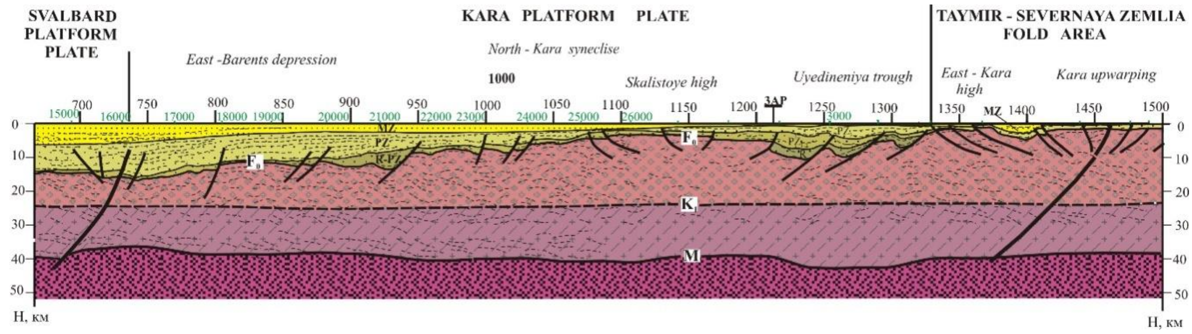

Figure 6. Section of the Earth's crust of the Kara platform and the Taimyr-Severozemelskaya fold zone (southeastern fragment of the AR-4 geo-traverse). Compiled using materials of State enterprise "Sevmorgeo" [8]. See Figure 2 for legend.

On the southeastern flank of the Kara plate, a large increase in the thickness of the platform cover up to 10 km is noted. Seismic features and solutions of the inverse problem of gravity and magnetic field interpretation in this part of the AR-4 geo-traverse suggest the development of a system of Paleozoic riftogenic structures in this area. These structures define the morphology of sedimentary strata typical for troughs.

The Baikalian folding epoch from the end of Proterozoic to the beginning of Cambrian is represented in the study area by structures of the Timan-Pechora, Taimyr, and Yenisei Khatanga fold zones.

The formation of the Timan-Pechora fold zone is associated with the Late Baikalian accretion of the passive margin of the Baltic palaeo-plate, Upper Pechora island arc, and the Bolshezemelskaya palaeo-plate. Since the Ordovician, the region has been developing as a passive margin of the Uralian palaeo-ocean. On tectonic schemes (Figures 3 and 4), a series of aulacogens is identified as linearly elongated depressions of increased mobility, limited by large faults and horst structures. Its deep structure is studied onshore along the DSS profile "Murmansk-Kyzyl" (Quartz) (Figure 7), and offshore—along the CDP AR-3 geo-transect.

There are four main structures identified in this region. The Timan mega zone corresponds to the Riphean rift of the passive margin of the Baltic, which underwent intense fold-thrust deformations with the uplift of Riphean sediments to the surface at the final stages of the Baikalian tectonic-magmatic cycle. The Izhma-Pechora mega block is also formed on the passive rift margin of the Baltic. Metamorphosed sediments of Riphean shelf up to 10–12 km thick are deformed here by Baikalian folds and thrusts and are overlain by the Paleozoic-Mesozoic platform cover. The Upper-Pechora mega zone with an anomalous (according to the DSS and other geophysical studies) structure of the Earth's crust is filled with deformed Riphean volcanic-sedimentary complexes of an island arc. During the Baikalian orogeny, these complexes were obducted on the margins of adjacent continental blocks. The Bolshezemelskiy mega block is interpreted as an ancient palaeo-plate of the continental type accreted to the Baltic at the final stage of the Baikalian tectonic-magmatic cycle. The overall tectonic pattern of the fold area is controlled by the dominant northwest-striking dislocations. The deep section shows the pinching out of most of the tectonic deformations within the upper crust (Figure 7).

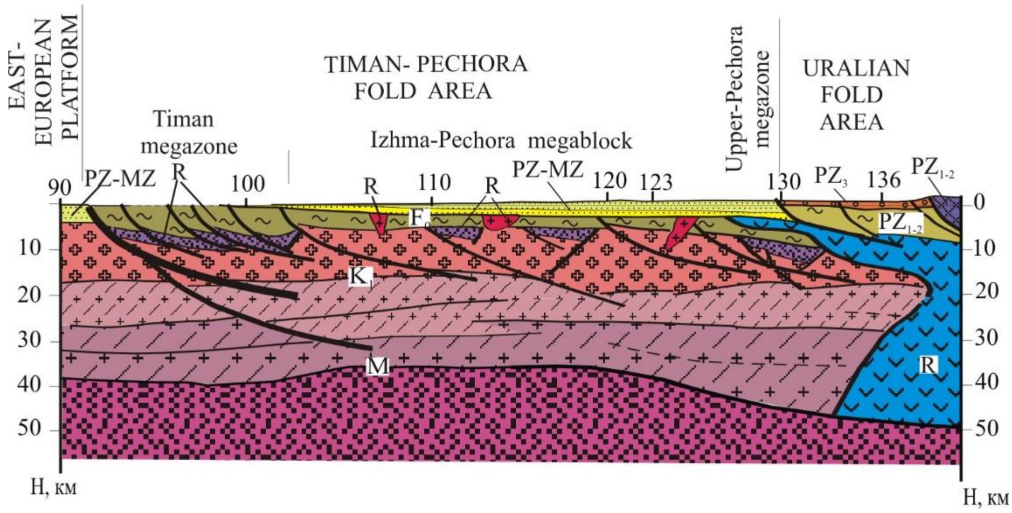

Figure 7. Section of the crust of the Timan-Pechora fold area (fragment of the "Murmansk-Kyzyl" geo-traverse). Compiled using materials from the Center «GEON» and VSEGEI. See Figure 2 for legend.

The Ural fold belt was formed in the process of the Hercynian orogeny (Late Palaeozoic) due to the accretion of Baltic and Kazakhstan palaeo-plates and a series of microplates and island arcs. The overall deep structure of this region is consistent with the model of collisional orogen of the Uralian type. Its distinctive feature is a series of microplates with continental-type crust and suture zones (Figure 8).

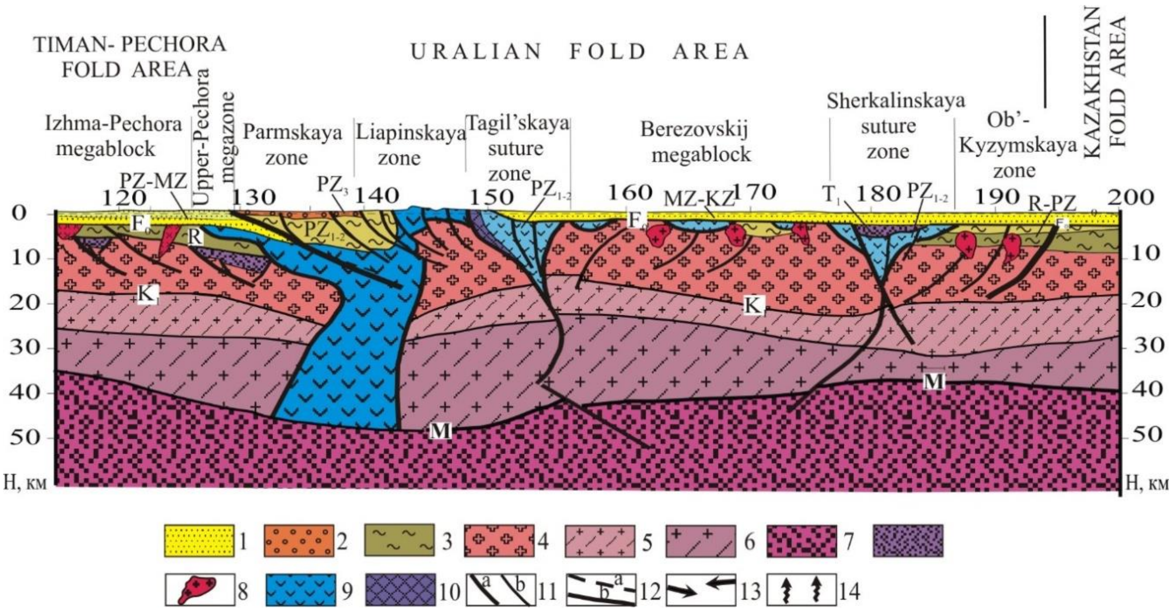

Figure 8. Section of the Earth's crust of the Ural fold zone (fragment of the "Murmansk-Kyzyl" geo-traverse). Compiled using materials from the Center GEON and VSEGEI. See Figure 2 for legend.

In the cross-section of the DSS "Murmansk-Kyzyl" profile, the Uralian fold area, from northwest to southeast, includes structures of the Western Urals: (a) intensely deformed margin of the Barents platform; (b) Tagilo-Magnitogorsk suture zone, modeled as a wedge-shaped synform filled with Paleozoic volcanic-sedimentary complexes; (c) the East Ural mega block overlain by sediments of the West Siberian geosyneclise on the Precambrian continental crust; (d) Sherkalin suture zone; and (e) Ob-Kyzym deformed margin of the Khanty-Mansi mega-block, which is a part of the Kazakhstan palaeo-plate.

The Central West Siberian fold area is fully covered by sediments of the West Siberian geosyneclise. Its formation is associated with the Late Paleozoic accretion of the Kazakhstan and Siberian palaeo-plates. The section includes the deformed margins of the Kazakhstan and Siberian palaeo-continents and the inter-block Irtysh-Zaysan suture mega zone at the site of the closed Asian palaeo-ocean.

The Taimyr-North-Zemlya fold area covers the area of the Late Paleozoic accretion of the Siberian and Kara palaeo-continents, which led to the formation of the Hercynian fold area and the deep erosion of the Ordovician-Devonian complexes [30]. The northern boundary of the orogen is the Late Paleozoic thrust front mapped on the islands of Severnaya Zemlya. The southern boundary is the Late Paleozoic fold structures of the Northern Taimyr, where intense thrust tectonics and the intrusion of post-collisional granites are documented. In northern Tajmyr, metasedimentary successions are partly magmatised and extensively intruded by 305 Ma age granites, which mark the age of the accretion of the Kara microcontinent to Siberia. Bio-stratigraphic observations indicate that the Severnaya Zemlya deformation took place in the latest Devonian to earliest Carboniferous. The Taimyr margin of the Siberian continent, defined by Zonenshain et al. [20] and Vernikovsky et al. [37] as the main Paleozoic suture, does not contain allochthonous oceanic terranes. Unconformably overlying Late Paleozoic continental and coastal-marine rocks of the Early Carboniferous-Permian age have been documented at some locations in the Severnaya Zemlya archipelago [4]. Thin Mesozoic poorly cemented sediments occur on the Paleozoic consolidated basement in this area.

Late Paleozoic to Early Mesozoic magmatic activity is manifested as mafic dykes and subordinate sills on Bolshevik Island. One K-Ar age definition of the intrusions (222 $\pm$ 15 Ma) is available [4]. Petrological and geochemical characteristics suggest a close connection of these rocks with the trap magmatism of Tajmyr and Siberia in Late Permian-Early Triassic time [4]. Jurassic and Cretaceous non-marine strata are documented in northern-most Tajmyr and many small islands in the Kara Sea [36].

The section along the AR-4 geo-traverse (Figure 5) shows the uplift of the Hercynian consolidated basement within the fold zone, and the development of a thin Upper Paleozoic-Triassic sedimentary cover. In the deepest troughs, the thickness of the sedimentary cover does not exceed 4 km. On the sides of the trough, the thickness of sediments decreases to the first hundreds of meters. A centriclinal system of faults is mapped in the section.

The Paikhoisk-Novozemelskaya fold area was formed at the initial phase of the Cimmerian tectogenesis (Late Triassic-Jurassic). The zonation of the fold area is not typical for a classical collisional orogen: it is located on the margin of the Svalbard Plate and does not have a distinct foredeep and suture zones. Here, the intensity of fold-thrust deformations decreases eastward, and metamorphism is confined to the zones of deep Main Novaya Zemlya and Central Novaya Zemlya faults. Fold-block and thrust dislocations occurred along these and similar fault zones. Numerous Middle Jurassic-Early Cretaceous paleontological occurrences in the northern part of Yuzhny Island of the Novaya Zemlya archipelago indicate the existence of a wide strait in this area at that time, and, therefore, the structural plan of the region at that time was strongly disturbed.

In the section of the AR-2 geotraverse (Figure 6), deep sediments of the western flank of the Paikhoisk-Novozemelskaya fold belt have a similar composition to those in the North Barents Basin, which allows us to define the long-term development of these structures as occurring in similar geodynamic settings of passive continental margin type.

The south-eastern flank of the profile intersects the structure of the South Kara sedimentary basin with a total thickness of the sedimentary cover up to 16 km. Judging by indirect geophysical characteristics (thickness of the crust, character of its layering, and velocity parameters), the basin is located on remnant oceanic crust. The basal part of the sedimentary layer is represented by the Paleozoic sediments of continental slope. They are covered by sediments of moderately deep seas and the volcanic-sedimentary formation of rifting basins (D_3-J_1). Continental and coastal marine clay-clastic Jurassic-Cenozoic sediments were identified in the upper part of the section.

The West Siberian young platform occupies the area of the West Siberian lowland and the shelf of the Kara Sea. Since the Mesozoic, this was a large area of subsidence filled with horizontally lying cover of Mesozoic and Cenozoic sediments, up to 4–6 km thick, overlying a strongly deformed basement. At the base of the platform sedimentary cover, there are Triassic volcanic-sedimentary formations that fill the rift system and complexes of the so-called "intermediate structural level (ISL)". Within Caledonian fold areas (Kazakhstan and Altai-Sayan), complexes of the late Paleozoic age belong to the ISL. On the Baikalian fold basement in the Yenisei Khatanga and Taimyr fold area, the ISL includes the full Paleozoic section. On the flanks of the Siberian platform, the ISL also includes Riphean deposits.

5. Tectonic Controls on Petroleum Potential of the Western Russian Arctic

Analysis of the petroleum resources distribution in the world's sedimentary basins of different genetic types confirms that the richest ones are the basins of young internal plates and folded-platform basins. The less rich ones are the large collisional basins of inter-mountain depressions superimposed on the central massifs, and the poor ones are the late and post-orogenic inter-mountain depressions on a folded basement.

Within the northeastern margin of the European Platform [36], some researchers identify a single heterogeneous Pechora-Barents Sea oil and gas basin (mega-basin) of the terra-aquatic type [12], while most others consider the Pechora and Barents Sea basins as two separate sedimentary basins.

These basins correspond to the domain of relatively stable long-term subsidence of the Earth's crust. The composition, structure, and burial conditions of sedimentary rock complexes of varying age that have formed during this process defined the formation, accumulation and preservation of commercially valuable oil and gas fields.

The Pechora-Barents Sea basin is an integrated dynamically developing system, in most of which sedimentation still goes on. The older sediment complexes are expressions of palaeo-basins. The generation, migration, accumulation, and conservation of hydrocarbons continue in this basin in corresponding thermodynamic regime. All these processes are inter-linked within the concept of oil and gas ontogenesis.

According to its structural-tectonic position, the Pechora-Barents Sea basin belongs to marginal-plate structures located at the forefront of the Ural and Paikhoisk-Novozemelskaya fold-thrust domains, and its development is linked to a stage of evolutionary growth of heterogeneous basins.

The Pechora-Barents Sea sedimentary basin also belongs to the category of peri-platform resonant formations to a certain extent, but it was formed on a younger basement in co-evolution with the Ural and Paikhoisk-Novozemelskaya fold-thrust areas. This ultimately determined the specifics of the sediment composition and many similarities and differences between the Western Arctic basins in spatial and depth distribution of hydrocarbons. The southern part of the Pechora-Barents Sea basin has formed on top of the pre-existing late Precambrian basin at the boundary of the Epibaykal plate. Its northern part has formed on the Epigrenville basement. This predetermined an active inherited tectonic development of the basin with up to 10–12 km thick sediments in the Timan-Pechora, and up to 16–18 km thick sediments in the Barents Sea parts.

The depth to heterogeneous basements of different ages (or to the bottom of non-dislocated platform swdiments) in the Pechora-Barents Sea basin varies from 0.5–1.0 km on its Western Kola-Kanin-Timan side, to 16–18 km, or possibly more, in the South Barents and North Barents basins. The reliability of interpretations, as reflected in the structural map of the basement surface, is higher onshore than offshore. In the Timan-Pechora sub-basin, the basement is accessible for drilling at 3–6 km depth in a large area, and the results obtained by geophysical methods are strongly linked to data from deep wells.

The complex of geophysical data allows us to confidently track the basement structures of the Pechora syneclise on the adjacent shelf at a depth of 6–10 km to the north towards the line connecting the Kanin peninsula and Mezhdusharsky Island. Further to the northwest, between this line and the South Barents rift we have identified a structural boundary limiting the area, within which the presence of the Baikal basement structures is still identified by some geophysical markers, but not by all of them.

The entire southeastern part of the Barents Sea (Pechora Sea), together with the adjacent area onshore, is a single structural element—the Pechora syneclise. The Pechora syneclise is bounded in the south-west by the slope of the Timan-Kanin ridge incorporating folded structures of the Baikalian age, and in the north-west by the flank of the South-Barents depression.

The Timan-Pechora region is commonly accepted as the area tectonically corresponding to the Timan-Pechora Epibaikalian plate and to peri-cratonal deepening of the consolidated baicalide structures that replace this plate in the East. These consolidated baicalide structures are covered at present by rock formations of the Ural trough, Paikhoisk-Novozemelskaya fold-thrust region, and Western and Axial (Central) mega zones of the Urals.

The western boundary of the basin, manifested by the chain of disjunctive folds of the Timan ridge, is the Western Timan thrust (suture rift). The Epibaikalian plate borders with the Epikarelian Russian plate: its eastern and north-eastern parts border the Main Urals and Baydaratsky deep rifts, respectively.

The Main Urals rift marks the boundary between (a) the Baikalian rocks submerged under the complex structures of the Western/Central Urals on predominantly continental crust, and (b) the Eastern Urals, where upper Proterozoic-Hercynian relics of the oceanic and island-arc crust are assumed to exist. The second rift, presumably of a shear nature, separates the Timan-Pechora basin from the South Kara basin of the West Siberian plate, which has a pre-Mesozoic basement that was repeatedly altered. The Northern limit of it may be the Kurentsovskaya flexure of the North Pechora Sea monocline, with a discharge-shift that is in contact with the Barents-North Kara sedimentary basin underlain by the Grenville-Baikalian basement.

The modern structure of the Timan-Pechora sedimentary sub-basin formed at the beginning of the Late Cretaceous, but the main stages of its formation were completed in the early Jurassic. The tectonic structure of the basin is determined by the final relationships of structural and formation divisions (structural floors and sub-floors). These relationships are characterized by structural maps of surfaces of corresponding divisions.

Given that the sedimentary cover incorporates several structural floors, a structural map of the diachronic surface of upper-Visean to lower Permian carbonates was selected for morphology-based tectonic zoning. It corresponds to the section of pre-orogenic structural floors that have formed during pre-orogenic (early and middle Hercynian) and orogenic (late Hercynian) stages of tectogenesis.

This map most adequately reflects the structural development of the Phanerozoic tectonic epochs. The upper-Visean–lower Permian carbonate complex, identified as an oil and gas-bearing one, dominates in the sedimentary cover in terms of initial total hydrocarbon resources. The diachronic surface of upper-Visean–lower Permian carbonates is a good seismic reflection horizon (RH I) and a reasonable approximation of the topography of the pre-orogenic carbonate strata on local anomaly gravity field maps. Dimensions and the subordination of tectonic elements determined their position in the hierarchical sequence. To justify zone boundaries, we have taken into consideration possible hydrocarbon migration paths and conditions of sedimentation.

A necessary condition for hydrocarbon generation, alongside the presence of enriched organic matter (OM) formations, is a certain degree of its catagenesis due to geothermal regime. The main geochemical parameters, alongside paleotectonic analysis, allow the identification of the formation and development of oil and gas maturation domains, as well as the identification of oil and gas accumulation areas in the Timan-Pechora region.

Modern assessment of the oil and gas potential of the Western Arctic is based on a complex of geochemical, lithology-facies, structural, and other studies. It also incorporates tectonic prerequisites and tectonic schemes created by a group of authors led by Dedeyev [13,38] and later modified for the purposes of oil and gas formation zoning [39].

The Barents Sea (BS) and Kara Sea (KS) belong to the Western-Arctic shelf. The KS shelf and the Yamal Peninsula form a single Yamal-Kara region (YKR), which occupies the northwestern part of the West Siberian mega-basin (WSMB) and the oil and gas-bearing mega province of the same name (WSMP). The shelf of the southern part of the Barents Sea (Pechora Sea) occupies the northern part of the Timan-Pechora oil and gas province.

The identified hydrocarbon potential of the Western Arctic seas of Russia as of 01/01/2019 is represented [40] by 19 fields, most of which are located within the Kara Sea bays. Some of them are shelf extensions of onshore fields, and some are located offshore in the Barents Sea.

All identified oil and gas fields are concentrated in two areas offshore: (1) the Barents Sea with mostly gas fields, and its southern part—the Pechora Sea, with mostly oil fields, and (2) the Kara Sea (mostly gas and gas condensate fields) [28,41]. The volume of proven oil reserves in these areas is relatively small: 454 million tons, 96% of which is concentrated in licensed fields. Projected oil resources are estimated at 12.8 billion tons, of which only 5% are concentrated in licensed areas [11,42,43].

Total proven gas reserves are much larger: 9.2 trillion m^3, of which almost 70% are in the fields that are partly covered by existing licenses [17,44–46]. The inferred resources of natural gas are estimated at 86.5 trillion m^3, of which only ~ 4% are located within licensed areas [34,42,47].

Until recently, the Barents and Pechora seas shelf was characterized by the highest level of geological and geophysical studies among the seas of the Russian Arctic, both at the regional and exploration stages. Regional and detailed 2D CDP seismic surveys covering more than 420,000 line km were carried out here. According to the results of geophysical studies, 75 structures of various degrees of investigation have been identified so far in the Barents Sea, excluding its southern part, the Pechora sea [42].

The basement of the Yamal-Kara sub-basin, which belongs to the north-western Arctic regions of the West Siberian mega-basin, has a Hercynian consolidation age (early Permian epoch) and is composed of a variety of strongly altered, mostly metamorphic rocks: clay shales, limestones, etc.

A large volume of regional seismic surveys has been carried out in the southern part of the Barents Sea (Pechora Sea) and in its junction with the onshore part of the Timan-Pechora province from 2008 to 2018. A significantly refined geological and geophysical model of the structure of the northern part of the Timan-Pechora oil and gas province, including its offshore extension into the Pechora Sea, has resulted from this work. A significant basis for the revision of the geological model of the lower Paleozoic section is the results of the parametric Severo-Novoborskaya-1 well.

As a result of our work, the sedimentary cover in this region has been subdivided into several seismo-stratigraphic complexes identified both onshore and offshore on the structural map constructed for the reflecting horizons (RH), such as VI (basement surface) (Figure 9), V-V1 (Silurian sole), IV (Silurian roof), III-IV (Silurian surface of different ages—Lower Devonian), III2 (Middle Devonian horizon), IIId (sole of Domanik—Middle Frasnian, Upper Devonian), IIIfm1 (Lower Famenian), IIv (Visean Carboniferous roof horizon), Ia (Lower Permian carboniferous surface), A-I (Lower Triassic roof), and B (horizon in Jurassic sediments) (Figure 10).

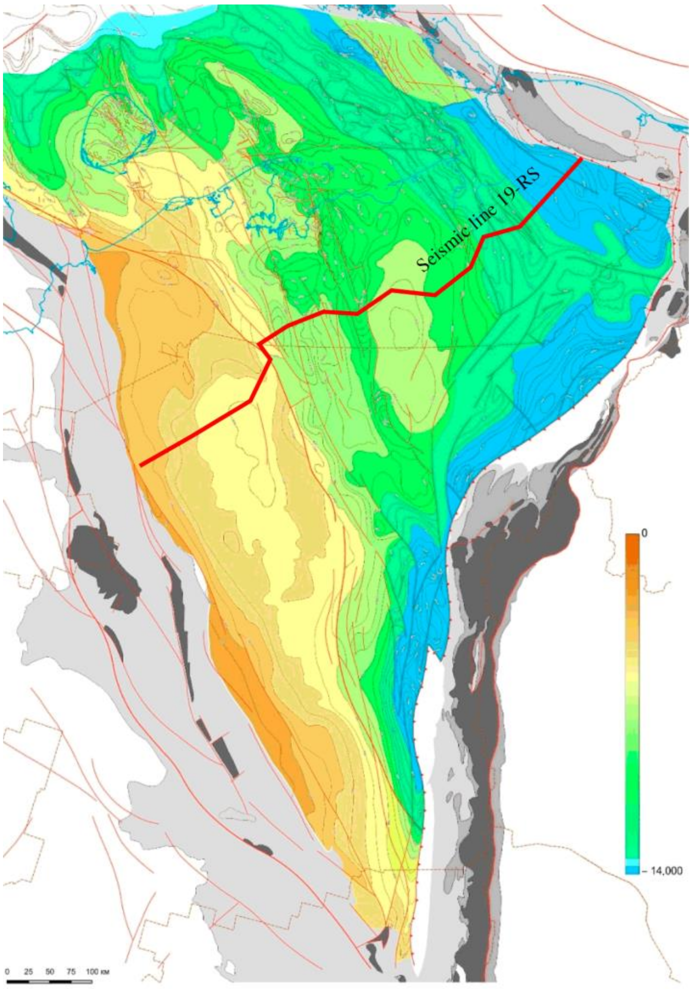

Figure 9. Structural map of the top of basement (RH VI).

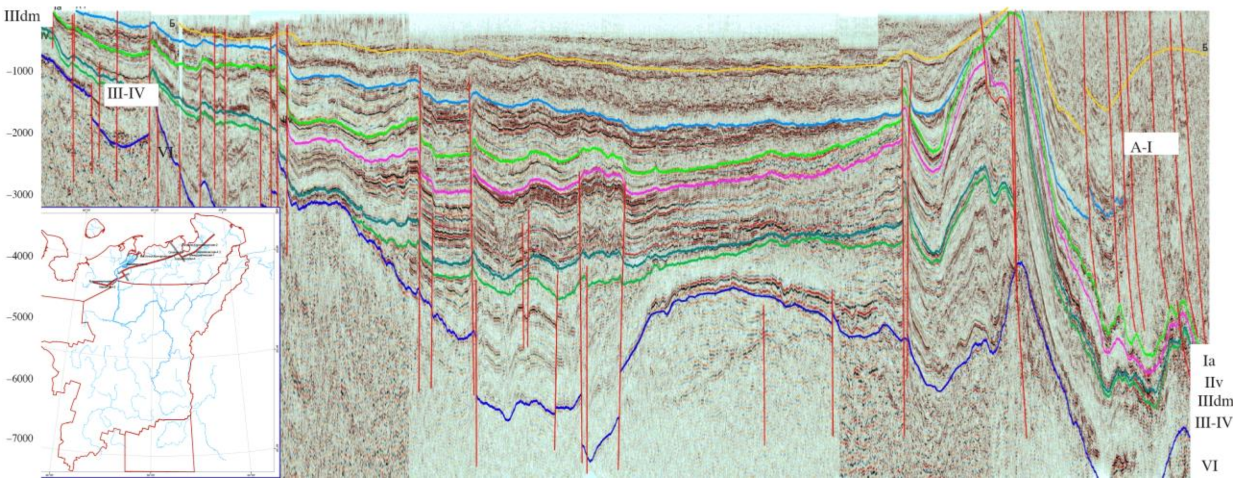

Figure 10. Composite seismic section through the main tectonic zones of the North of the Timan-Pechora sedimentary basin, after [41].

The seismo-geological model thus obtained was used to refine the tectonic and oil and gas zoning of the North of the Timan-Pechora province, including the Pechora Sea.

As a result, we have improved the locations of the boundaries of the main tectonic elements (top-order structures), such as north of the Izhma-Pechora syneclise, the Malozemelsk-

Kolguev monocline, north of the Pechora-Kolvinskoe aulacogen, the Horeyversko-Pechora sea basin, the North-Pechora sea monocline, the pre-Paikhoisk-pre-Yuzhnovozemelsky depression (see Figures 10 and 11) deflection, and the Gulyaevsko-Varandeyskay structural-tectonic zone. These improvements relate mostly to the offshore part of the study area, and they have allowed us to establish the hierarchy of the refined boundaries based on their relationship.

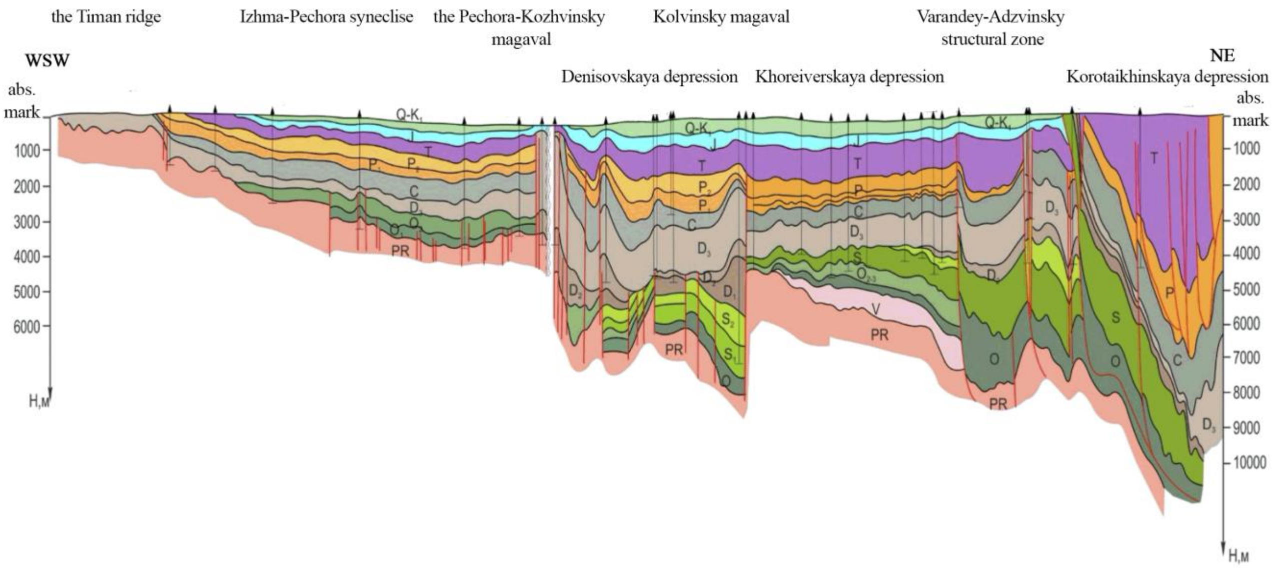

Figure 11. Regional geological section along seismic line 19-RS (see Figure 9) through the main tectonic zones of the Central part of the Timan-Pechora sedimentary basin, after [41].

There is a discrepancy between the structural plans of the sedimentary cover surface and the surface of Permian carbonates (Figure 9), which determines significant differences in oil and gas content controlling factors on different structural floors. A broad presence of basal deposits of the early-middle Ordovician age, probably terrigenous, has been discovered in the western part of the sedimentary basin.

Contrary to this, at the base of the sedimentary cover in the Pechora-Kolvinskoe aulacogen (rift) and Varandey-Adzvinsky structural zone, development-sustained carbonate deposits (platform carbonates) with high oil-generating potential have been identified, thus determining the prospects of the continuation of the Timan-Pechora province to the Arctic shelf.

Our research has substantially improved understanding of the structure and volume of pre-inversion (riftogenic) sediments for the following structures: (1) the outer part of the Pechora-Kolvinskoe aulacogen and its marine continuation (age O_{2-3}, S_{1-2}, D_{1-2}), (2) uncompensated troughs developed along the Timan ridge and the Kanin uplift and filled with terrigenous sediments (age Є, O_{1-2}), and (3) a trough that bounds the sedimentary basin in the north and that was filled with relatively deep-water sediments of domanik type (age D_3–C_{1t}) in the late Devonian-early Carboniferous time. As a result, the evaluation of the oil and gas potential of the whole region has been significantly modified.

Quantitative assessment of oil and gas potential is based on geological understanding of sedimentary basin evolution, source rock characterization, oil and gas-bearing strata in these basins, as well as regional, zonal and local characteristics of the region that enable a reasonable forecast and refinement of already identified hydrocarbon potential. The most significant confirmation of the prospects comes from already booked reserves of the identified fields based on drilling and, indirectly, on seismic data.

A series of studies targeting improved assessment of the oil and gas potential ("quantitative assessment of oil and gas resources") of Russian regions (as of 01/01/2017) has been completed. This assessment, carried out by VNIGNI, VNIIOkeangeologiya, and VNIGRI [48], covers all prospective oil and gas-bearing basins, including the Western Arctic regions of Russia.

Private oil and gas companies operating onshore, and two companies that are part-owned by the State (Gazprom and Rosneft) and have exclusive rights to work on the Arctic shelf, conduct their internal assessments of the hydrocarbon potential. However, their estimates often relate exclusively to areas of existing licenses or prospective licensing areas that companies consider to be priorities for development.

Preliminary results of the official quantitative assessment of the resources of the Arctic, offshore and onshore, have already been published [7,21,34,42,47,49–52], and in this paper, they are presented to characterize the oil and gas potential of the sedimentary basins under consideration [11,28,40,41,43].

The quantitative assessment of resources of poorly studied and complex areas of the Arctic [17,44–46] is a result of research by geologists who were able to build a system of concepts about the geological evolution of these areas on a basis of fragmentary regional geological and geophysical data, and to construct models of geological structure of sedimentary basins that define hydrocarbon potential [53].

6. Discussion: Assessment of the Resources of the Western Arctic Shelf

By any measure, the petroleum potential of the Russian sector of the Western Arctic is unique, both in terms of the volume and diversity of its composition, as proved by discoveries of unique, giant, and large oil and gas fields onshore. More than 50 giant and large fields have been identified in this territory. To develop projects in the Western Arctic and to exclude purely market-related factors, it is necessary to carry out special research aimed at obtaining new geological and geophysical information for a more objective assessment of petroleum potential, and to take into consideration the experience of international and Russian experts.

The best-known estimates were made by the consulting companies Wood Mackenzie and Fugro Robertson in 2006 [54], and USGS—United States Geological Survey in 2008 [55], which conducted two special studies of the hydrocarbon potential of the Arctic.

USGS has analyzed 25 out of 33 Arctic basins, including two primarily onshore areas of the Western Arctic—the northern part of the Timan-Pechora Basin and the northern part of the West Siberian Basin and three offshore areas of the Northern (Norwegian) Barents and Kara seas: (1) the East Barents Sea, (2) Barents Platform, (3) and North Kara Basins and Platforms (Figures 12–14). The deep-water Eurasian basin limits the basins of the Western Arctic from the north in these studies.

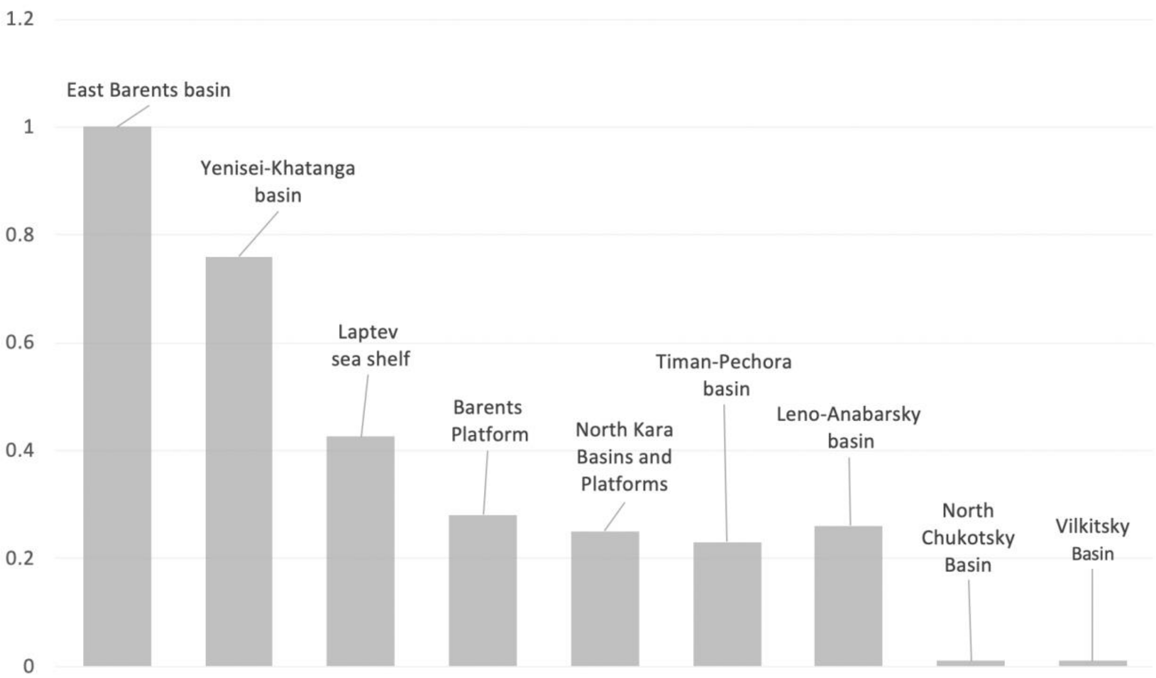

Figure 12. Estimation of oil resources in the Arctic basins of Russia (according to the United States Geological Survey (USGS) data [54]), billion tons.

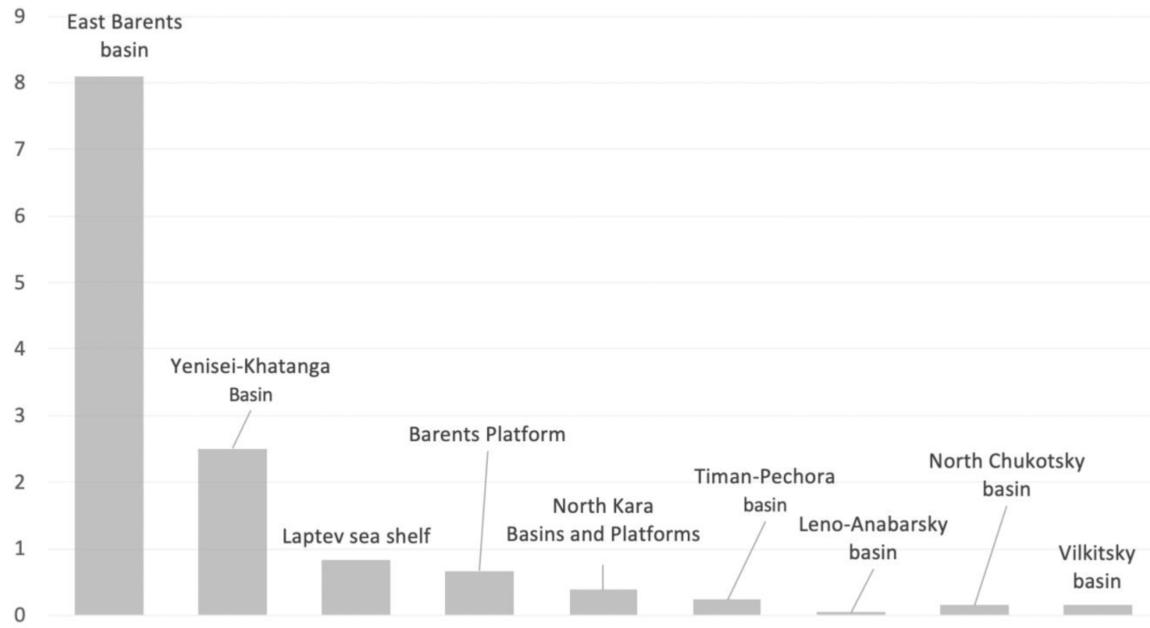

Figure 13. Estimation of gas resources in the Arctic basins of Russia (according to the USGS data [54]), trillion m^3.

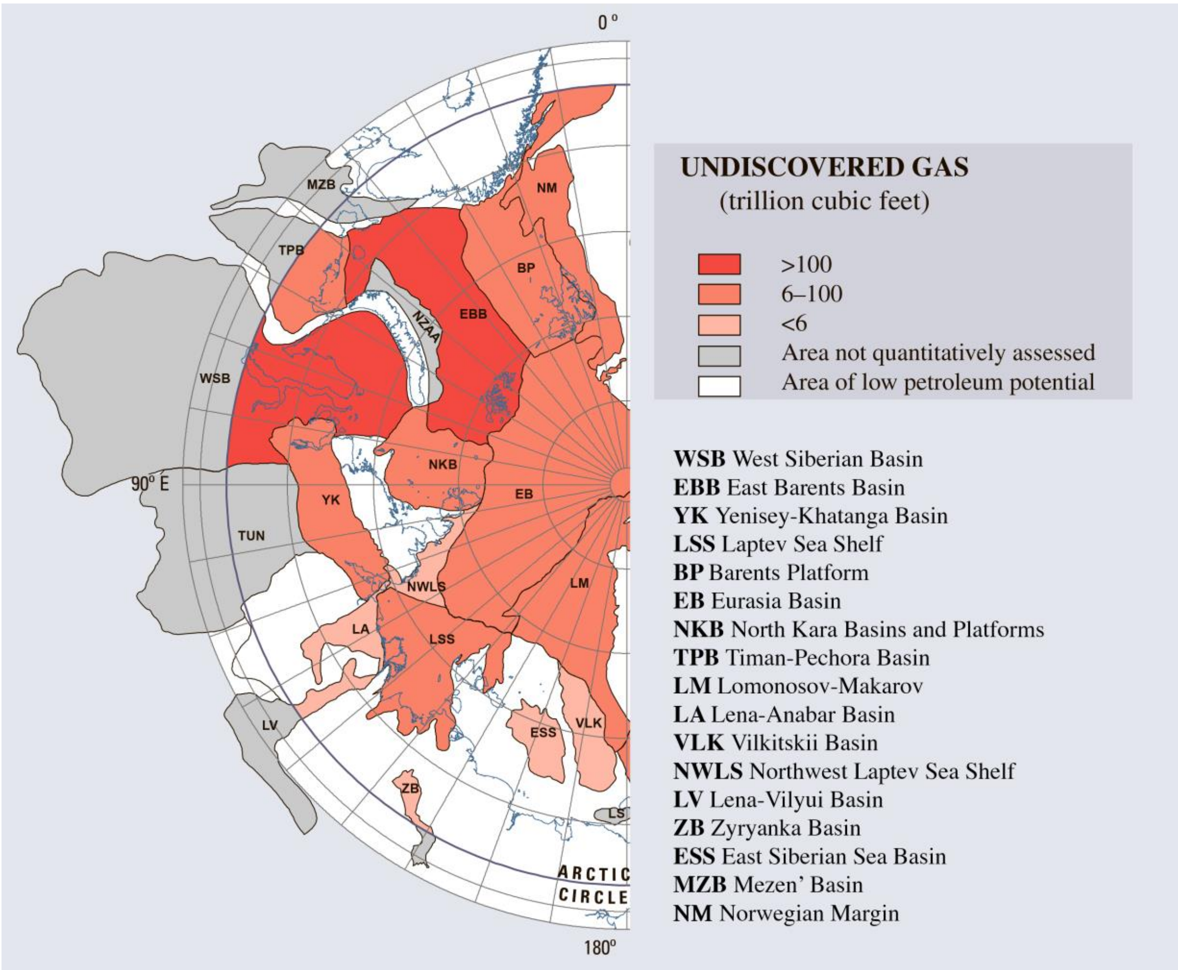

Figure 14. Provinces in the Circum-Arctic Resource Appraisal for mean estimated undiscovered gas, after [54].

Different approaches were used in [54] and [56]. For the purposes of our analysis, we have converted petroleum potential estimates of [54] and [56] originally presented in barrels for oil/oil equivalent (o.e.) and in cubic feet for gas to, more commonly used in Russia, tons and cubic meters, respectively. We have used the following conversion coefficients: 1 barrel of oil = 0.14 metric tons of oil [57]; 1 barrel of oil equivalent = 0.1462 tons of oil equivalent [58]; 1 billion cubic feet of natural gas = 25,199.58 tons of oil equivalent [58].

The Wood Mackenzie and Fugro Robertson report [54] is based on a detailed analysis of geophysical and seismic data in various Arctic basins. According to this study, the undiscovered oil and gas resources of the Arctic are estimated at 233 billion barrels of oil equivalent (o.e.), or more than 30 billion tons o.e. A total of 85% of the proven reserves and 74% of the expected reserves (resources) are gas.

In the USGS study [56], the main emphasis was on probabilistic geological analysis and the identification of zones that are likely to contain relatively large oil or gas reserves (more than 50 million tons).

The total volume of undiscovered oil and gas resources in the entire North of the Arctic Circle region is ~412 billion barrels of o.e., or ~22% of the total undiscovered reserves of conventional hydrocarbons in the world. This is almost double the Wood Mackenzie/Fugro Robertson estimate [54].

Undiscovered oil resources were estimated at ~90 billion barrels of oil, or 12.3 billion tons at 0.862 t/m^3 conversion density. That amounts to ~7% of the world's resources.

Undiscovered gas resources were estimated at ~1669 trillion cubic feet of gas (~47.2 trillion m^3) and 44 billion barrels of natural gas condensate (or 5.5 billion tons (at 0.780 t/m^3 conversion density).

The total estimate of the Arctic hydrocarbon resources according to [54] was ~65 billion tons of o.e.

At the same time, the share of comventional oil, including liquid fractions of natural gas (NGL), in the USGS study [56] accounted for about 134 billion barrelss (or 17.8 billion tons of o.e.). That is 13–15% of the world's total resources [55]. Conventional natural gas accounts for the remaining ~279 billion barrels of o.e., or just under 30% of the world total gas resources.

It is important to note that about 80% of the Arctic resources are confined to a relatively shallow shelf (less than 500 m water depth). Moreover, USGS estimates that the probability of finding any significant hydrocarbon reserves in the Central Arctic ocean, as well as in the surrounding areas, is close to zero.

According to our analysis of USGS data (see Table 1 in [55]), Russia accounts for approximately 70% of the total undiscovered gas resources in the Arctic, with the main prospective areas located in the north of the West Siberian basin including the southern part of the Kara Sea, with estimated resources of 18.5 trillion m^3, and East Barents Sea (9.0 trillion m^3).

According to [56], Russia has ~30 billion barrels of o.e. (estimates for all Arctic basins of the Russian Federation), or 33% of the total Arctic oil resources, with 7.4 billion barrels of o.e. localized in the southeastern part of the Barents Sea. A total of 3.7 billion barrels of o.e. are expected in the West Siberian Basin, 2.0 and 1.8 billion barrels of o.e. in the deep-water part of the Barents and Kara seas, and 1.6 billion barrels of o.e. in the Timan-Pechora Basin.

The share of liquid hydrocarbons in the Western Sector of the Russian Arctic increases up to 41% of the total resources of the entire Arctic if 3.7 billion tons of natural gas liquid (NGL) resources are added.

Thus, the total technically recoverable resources of the Russian Arctic sector are estimated by USGS at about 40 billion tons o.e., of which only 4.3 billion tons are oil, more than 32 trillion m^3—gas, and about 3.7 billion tons o.e.—condensate.

A more modest estimate of hydrocarbon resources of the Russian Arctic (76.3 billion tons of o.e) was presented by the World Energy Agency (WEA) [59,60]. According to the WEA, the recoverable part of crude oil resources in the Russian sector does not exceed 9.6 billion tons of o.e., and gas resources are estimated at a modest 21.4 trillion m^3. Thus, the total estimate of recoverable resources for the Russian Arctic without condensate is only 31 billion tons of o.e. [40].

The same study shows that a total of 61 major oil and gas fields have already been discovered north of the Arctic circle, with 43 of them in Russia (today there are more than 50 of them according to our data), 11 in Canada, 6 in Alaska, and 1 in Norway, which also indicates the dominance of the Western Arctic in the structure of existing discoveries.

According to UN estimates [61,62], oil resources of the entire Arctic are estimated at 140–180 billion tons, of which almost 40% are in the Eastern part of the region, and about a third are located between the North Pole and the American continent. Thus, according to the UN estimate, the potential of the Western Arctic is 40–45 billion tons of o.e. UN experts stated that, given the huge technical difficulties in the development of these resources, the economic feasibility of Arctic projects is highly questionable [3].

There are serious concerns that the official resource assessment [40,41,63] may be biased due to over-reliance on the official point of view about the huge potential of the Arctic [40]. This conclusion is based on the fact that estimates of the petroleum potential of the least explored parts of the Arctic shelf in the last 20 years show a steady increase, regardless of the increase in the knowledge database, the number of new important discoveries, or the development of fundamentally new ways of increasing the hydrocarbon resource base. Additionally, it is not possible to obtain new core material for geochemical studies that could improve estimates of the petroleum potential and could indicate its underestimation.

For example, the total hydrocarbon resources of the richest Western Arctic shelf, according to the official estimate as of 01/01/1993, were at 75.3 billion tons of oil equivalent [21,34]. The next estimate (as of 01/01/2002) showed an increase of 7.26 billion tons of oil equivalent, comprising 0.26 billion tons of oil equivalent increase for the Pechora Sea, 1.9 billion tons of oil equivalent increase for the Barents Sea, and 5.1 billion tons of oil equivalent increase for the Kara Sea. The estimate as of 01/01/2009 showed a further increase in resources (17.5 billion tons of oil equivalent), resulting in the total evaluation of oil and gas resources of the offshore Western Arctic region at more than 100 billion tons of oil equivalent.

The last, recently completed, 2020 assessment consolidated the volume of hydrocarbon resources of the Western Arctic basins at 101 billion tons of oil equivalent, including 55.3 in the Barents Sea and 45.7 in the Kara Sea [64,65].

The above-mentioned increase in resource estimates is paradoxical: we observe a significant decrease in the ratio of drilled and proven reserves to the overall assessment of the petroleum potential of the region against the background of a significant increase in geophysical, including seismic, studies [66].

Such conclusions are especially paradoxical in the Pechora Sea area, where the latest identification of the new deposits goes back to 1993–2002, but a significant resource estimate increase occurs at a time when there were no discoveries (2002–2009). Such inconsistencies make us more careful and reserved about the assessment of resources at the present time.

Completed quantitative assessment of oil and gas resources is based on modern ideas about the tectonic structure of sedimentary basins of the Western Sector of the Russian Arctic, as well as on the new data about the volume of sediments and source rock potential, and also on comparative analysis on existing discoveries (the method of geological analogy). This assessment indicates a greater potential for both oil and gas.

The volume of forecast hydrocarbon resources (oil, free gas, condensate, and dissolved gas) of the Russian Arctic is estimated at 250 billion tons of oil equivalent, including ~43 billion tons of oil and condensate (17% of all resources) and ~206 trillion m^3 of natural gas. The distribution of hydrocarbon resources within the prospective regions onshore and offshore the Russian Arctic is very uneven (Figures 15–17). The onshore accounts for ~136 billion tons of oil equivalent (almost 55% of the total amount), of which the vast majority are gas-containing fields located administratively in the Yamal-Nenets Autonomous district (120 billion tons of oil equivalent, including 97 trillion m^3 of gas). The remaining 45% is also mostly gas dispersed within the Arctic shelf.

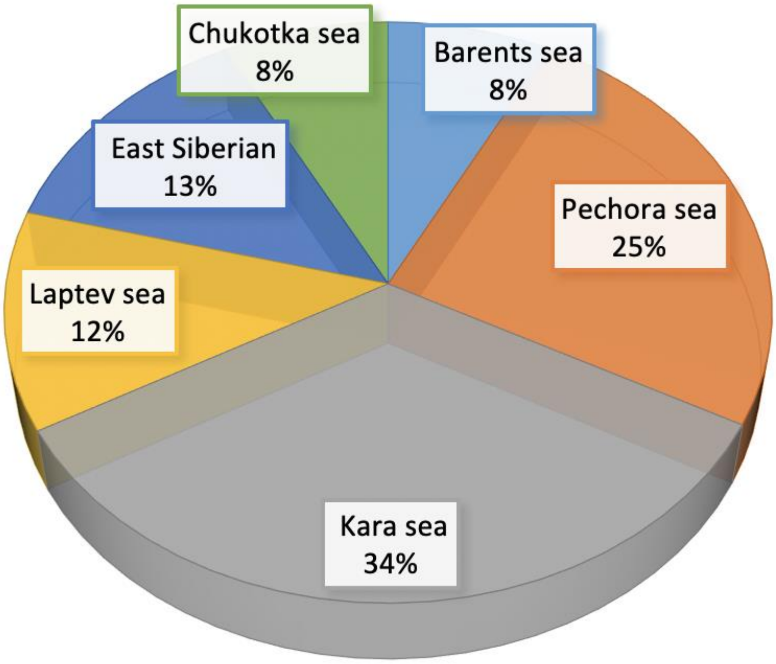

Figure 15. Distribution of oil resources in the Arctic seas of Russia.

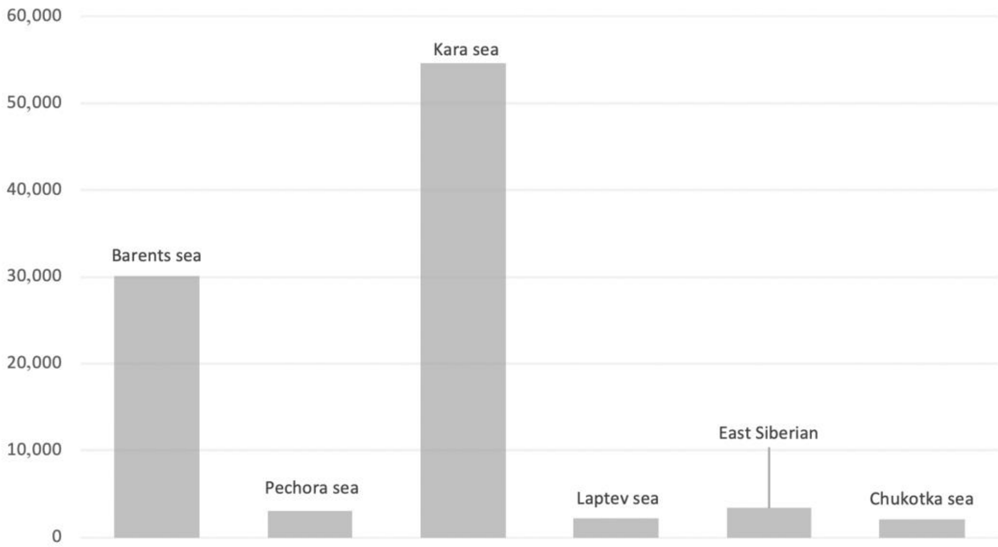

Figure 16. Distribution of initial total free gas resources of Russia's Arctic seas, billion m^3.

The total potential of the Western Arctic of the Russian Federation is estimated by us at 13.4 billion tons of liquid hydrocarbons (oil and gas condensate) and 86.7 trillion m^3 of gas.

Most of the liquid hydrocarbons are predicted in the shallow water extension of the Timan-Pechora and West Siberian sedimentary basins (the Pechora Sea—5.5 billion tons, the southern part of the Kara Sea—2.0 billion tons).

The estimated potential of the northern part of the Timan-Pechora basin onshore exceeds 5.5 billion tons of o.e. This estimate reflects the most up-to-date level of geological and geophysical studies and exploration. More than 2.0 billion tons o.e. of recoverable oil and gas reserves are in the identified fields, including producing fields [40].

International resource assessments heavily emphasize technological resource availability and the economic feasibility of exploration and development. Taking this into account, resources of shallow water continuations of the Timan-Pechora and West Siberian oil and gas provinces are estimated highly enough.

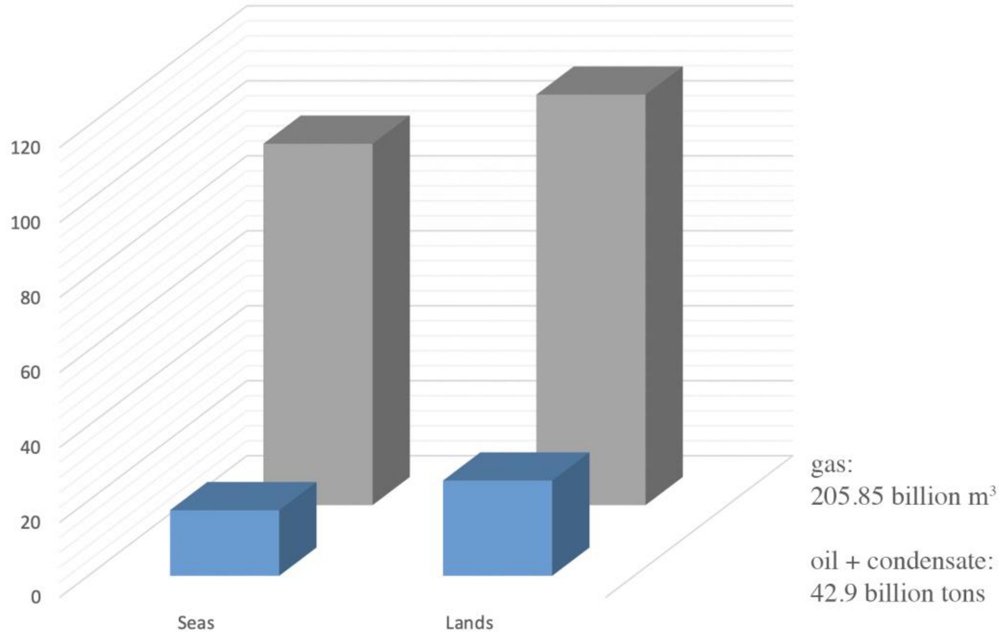

Figure 17. Distribution of oil and gas (free plus dissolved) resources in the Arctic zone of Russia according to the quantitative assessment as of 01/01/2019, after [40].

In summary, estimates of poorly explored sedimentary basins of the Arctic shelf remain controversial, both in terms of overall potential and phase composition ratio.

Some debate was caused by the assessment of the petroleum potential of the offshore continuation of the West Siberian province. According to a group of researchers, the main undiscovered gas resources of the Arctic zone [67] of this province are concentrated in the Aptian, Neocomian, and middle Jurassic, including the Kara Sea, and they can reach 33–43 trillion m^3.

The following discoveries are predicted: (1) 3 to 4 supergiant (more than 1 trillion m^3) fields in the open shelf area, (2) 22 to 25 largest and giant (0.1–1.0 trillion m^3) fields, (3) 70 to 80 large (30–100 billion m^3) fields, and (4) several hundreds of medium and small fields.

7. Conclusions

1. The tectonic development of the Western Arctic determined the formation of sedimentary basins characterized by high oil and gas potential.
2. The accumulation of oil and gas source rocks and the formation of reservoirs occurred mostly at initial divergent stages of basin evolution. In the Timan-Pechora basin, this happened in Silurian-Tournaisian.
3. Formations of convergent stages in most cases contain only natural gas reservoirs.
4. Some source rock formations in the Timan-Pechora basin have entered or passed through the oil and gas generation windows, which resulted in a significant scale of hydrocarbon generation and migration.
5. The position of oil and gas generation windows within various accumulation zones in the main oil and gas complex, in general, favorably coincided with stages of their formation and led to the large-scale formation of palaeo-zones of oil and gas accumulation.
6. The generation of hydrocarbons in the Timan-Pechora basin, including its northern part (Pechora Sea), was completed at the end of Triassic, but its structural evolution and subsidence extended post-Triasic.

7. Three genetic types of free gas accumulations are distinguished in the Timan-Pechora basin: (1) gas sourced from Permian-Triassic mixed organic matter of the waters; (2) gas of modern active uplift zones at relatively shallow depths that can be genetically associated with any catagenesis zone; (3) gas formed at favorable conditions of the final catagenesis and apo-catagenesis stages that is mostly associated with depressions.
8. Estimates of the petroleum potential of the Western Arctic vary broadly—from 34.7 to more than 100 billion tons of oil equivalent, with the share of liquid hydrocarbons from 5.3 to 13.4 billion tons of oil equivalent, and the condensate share from 8.0 to 13.4 billion tons of oil equivalent.
9. Gas dominates in the Western Arctic, with oil accumulation zones restricted to the offshore part of the Timan-Pechora basin, and condensate accumulation zones to the offshore part of the West Siberian basin on the Kara Sea shelf.
10. Large discrepancies in the assessment of discovery structure and in the petroleum potential estimates reflect the uncertainty of experts, probably caused by a lack of experience in work with an extremely low knowledge base.

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On the Rheological Properties of Thermodynamic Hydrate Inhibitors Used in Offshore Oil and Gas Production

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Abstract: A new thermodynamic hydrate inhibitor (THI), is being proposed based on the analysis of its rheological properties leading to improvement of the injection process. The method is based on the viscosity changes during the injection process. The experimental tests analysing the viscosity, shear stress related to drag force of the MEG and ethanol mixture allowed us to develop a better injectable THI. Considering the results that we obtained, it can be said that the mixture of MEG/EtOH is more convenient for transportation and injection process, and also to be stored on the platform. The use of ethanol and MEG mixture as THI is novel in this field. It turns out that the benefits of the mixture overcome the benefits of using them alone. This discovery opens a window for more improvements to natural gas hydrate suppression. The mixture could also change the formation of gas hydrates, thereby destabilizing the ice-like structure. Since the hydrate suppression process is stoichiometric—directly proportional to water production—it is necessary to inject large amounts of THI, thus improving the injection with the proposed mixture could lead to a more economical process.

Keywords: MEG; ethanol; thermodynamic hydrate inhibitors; umbilicals; chemical injection system

1. Introduction

1.1. Gas Hydrates Overview

Offshore oil and gas production lately has gone to facilities further from the coast and to deeper sub-sea production systems. These characteristics have conditioned the technology and equipment necessary to allow the production to continue flowing without issues. In these locations, where the working pressures are very high and the temperatures are low, the formation of gas hydrates inside the production systems is quite frequent. Gas hydrates form when gas molecules are inside ice-like lattice and are tied with water molecules by van der Waals forces. These forces make the gas hydrate very stable. Due to the low temperature these water molecules, the hosts, get frozen trapping the gas molecules, the guests. The variety of the gas hydrates depends primarily on the size and concentration of the guest molecules, as can be seen in Table 1.

Table 1. Gas hydrates structures and guest molecules.

Structure I	Structure II	Structure H
Methane Ethane Carbon Dioxide etc.	Propane Iso-butane etc.	Methane+Neohexane Methane+Cycloheptane etc.

1.2. Methane Hydrates Potential by Global Regions

In gas and oil production the hydrates are mostly formed with methane as a guest molecule. This is one of the reasons why the investment interest in methane gas hydrates has been growing, as it represents another option for the energy market, with average world resource potential of 43311 TCF. The regions with the most methane hydrates exploitable zones can be seen in Figure 1. They are all over the globe. It can be seen that some regions such as North (21.37%) and Latin America (11.41%) have a big portion of the resources, among the Arctic (15.29%) and former Soviet Union (8.84%).

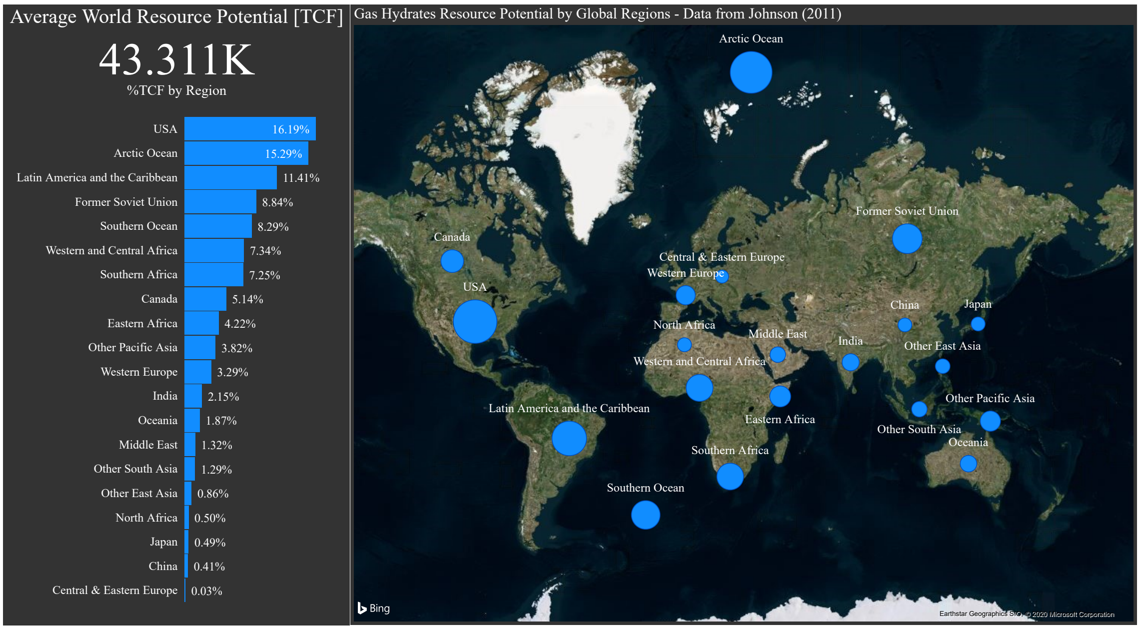

Figure 1. Methane hydrates resource potential by global regions [TCF]—Data from Johnson (2011) [1].

As methane hydrates can be encountered all over the world, it means that the problems related to gas hydrates follow and may develop in any of these zones. The problem with the formation of gas hydrates is not just the reduction of the production flow rate to the extreme of stopping the flow [2–5]. Also, the fact that once the ice structures are formed, the upward production along with the decreasing pressure going up, these structures can become on-ice projectile that would cause damages to the sub-sea production systems, the flowlines, Pipeline End Manifolds (PLEMs), Pipeline End Terminations (PLETs), In-Line Tees (ILTS), connectors, valves, jumpers, etc. Other problems that may happen during oil and gas production in zones where gas hydrates are present are an uncontrolled gas release while drilling, damage to the well casing. Also, the disruption of a gas hydrates sediment could fracture the seafloor compromising the stability for the wellbore among other sub-sea equipment on the sea floor [6].

1.3. Inhibition of Gas Hydrates

There are several methods used to avoid the formation of gas hydrates, the injection of THI being one of the most-used at the moment. The injection of THI is done using a chemical delivery system.

In some cases, it is continuous through capillary systems installed on completions systems. The use of THI is a common practice, as they allow the production of oil and gas under harsh conditions with reduced risks and increased safety.

The main characteristic of the THI is that they shift the hydrates formation conditions towards higher pressures and lower temperatures, like the ones encountered under normal production circumstances [7,8]. Some of the most used THI are MEG, methanol and ethanol. Some advantages of using methanol when comparing it with MEG include higher hydrate suppression and lower viscosity. Unfortunately, it is more contaminant for downstream processes and also more strict environmental regulations. On the MEG side, it is highly recoverable and reusable, small losses to the hydrocarbon phase but due to its high viscosity, transporting MEG needs more powerful pumping system [9].

Figure 2 shows the usual change a gas hydrate formation scenario has under the effect of THI, such as MEG, methanol or ethanol. As it can be seen, the hydrates formation curves move to the left when injecting said proportion of THI. The influence of the quantity of the THI injected can also be seen. The more THI is injected, the further left the curve shifts, i.e., to a condition of higher pressure and lower temperature needed for the gas hydrates to be formed.

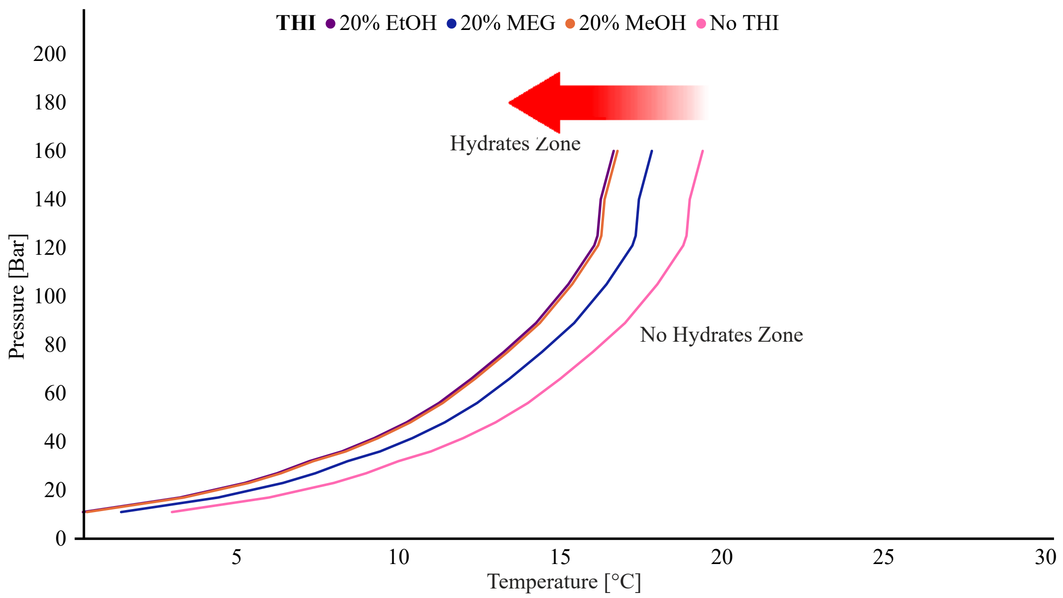

Figure 2. Hydrate formation zones shift caused by the use of 20% of THI—Adapted from Kim (2018) [10].

The No THI hydrate curve was adapted from Kim (2018) [10]. The composition of the fluid can be found in Kim (2018) [10]. The curves considering 20% of THI were calculated using the Hammerschmidt method, Equation (1). The data for these curves can be found in Table A1. Figure 2 demonstrates the effect of the THI decreasing the temperature and shifting the curves. In this case, we used a 20 wt% of mentioned THI. Hammerschmidt Equation as is shown in Equation (1) [11].

$$DT = K * W / M * (100 - W) \quad (1)$$

where:

DT Temperature shift, hydrate depression [°C]
K Constant, from Table 2
W Concentration of the inhibitor in weight per cent in the aqueous phase
M Molecular weight of the inhibitor divided by the molecular weight of water, from Table 3

Table 2. K-value for Hammerschmidt equation found in literature [12,13].

THI	Methanol	MEG	Ethanol
K-value	1297	1297–2222	1297

As seen in Figure 2, the area to the right of the curve will be free of hydrates, whereas the area to the left represents conditions of pressure and temperature where hydrates can form. The K values for methanol MEG and ethanol used to calculate the temperature decrease using the Equation (1) were 1297, 1500 and 1297, respectively.

1.4. Chemical Delivery of THI

Figure 3 shows a general configuration of a chemical injection system, consisting of tanks, pumps and control panel. When using chemical injection systems, MEG is usually injected into the borehole directly through valves [14]. Methanol can be injected at the Christmas Tree to prevent freezing of the line in a start-up condition. MEG is also injected directly into the flow lines during normal operation [15].

The logistics of these treatments can be highlighted as follows:

Taking the THI from shore to platforms where they are being stored in tanks. The temperature and pressure of the tanks need to be controlled. Their volume depends on the injection rate, usually with a margin to assure the treatments. It is important that the tanks be redundant to enable cleaning/repair without platform shutdown [10]. It is also important to avoid corrosion and to be reactive to the injection fluids.

Using a pumping system to take them to the bottom of the sea using umbilicals. Pumps are usually displacement-type pumps. It is necessary to be able to give as much pressure as the flowing pressure when injecting to the well. In the other case, it should be platform design pressure when injecting to the export line [10]. As we are dealing with pumps, narrow pipes (umbilicals for MEG injection usually are 1/4–3/8 inches), high pressure, high to low temperatures. Characteristics taken into account are viscosity, density, chemical compatibility of the injection fluids, among others.

Besides these two, other components are important in the chemical delivery system. The control panel used to control the pumps, valves, and also items like pressure gauges and transmitters for the pumps and tanks, reduction valves, bypass sections, etc. A downhole continuous chemical injection system can be used to inject the fluids into the well or directly into the production flowlines.

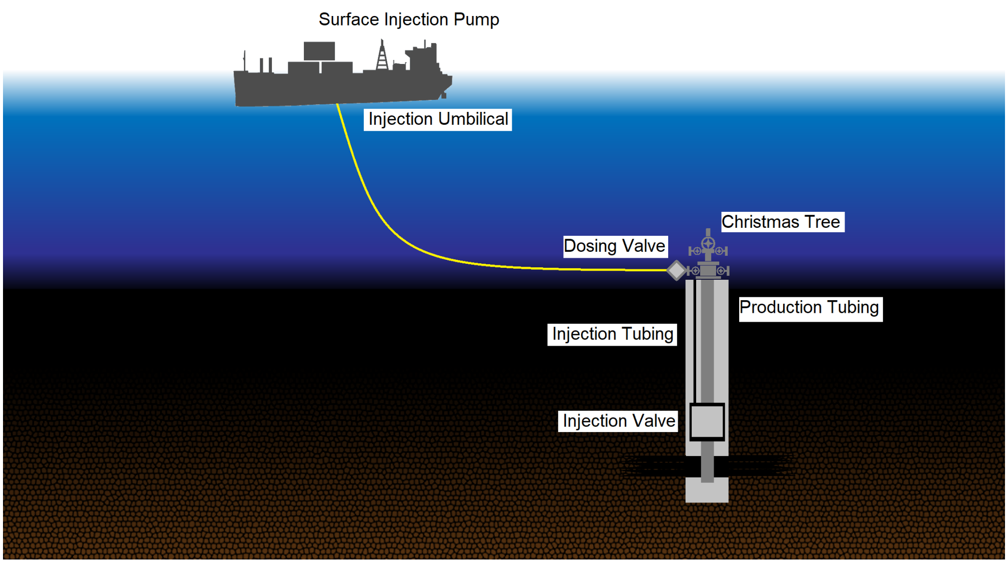

Figure 3. Schematic of an offshore downhole chemical injection system.

1.5. Safety of THI

When working with THI, some considerations need to be made to assure safety and low operational risk on platforms. Methanol has a low flash point, as shown in Table 3, making it easily flammable. Unfortunately, when burning its flame is smokeless and almost invisible during the day. On its behalf, MEG is non-flammable. Methanol is toxic and a classified hazardous chemical. Since pressure is a big player in offshore production, vapour pressure is a characteristic to be considered. Due to its high vapour pressure, it is easy to inhale, causing breathing problems [16,17].

Table 3. Properties of fluids.

THI	Methanol	MEG	TEG	Ethanol	Water
Formula	CH_3OH	$C_2H_6O_2$	$C_6H_{14}O_4$	C_2H_5OH	H_2O
Molecular Weigh [g/mol]	32	62	150	46	18
Density [Kg/m^3]	792	1116	1126	789	997
Viscosity 25 [°C] [cp]	0.5	18	36	0.9	0.89
Freezing Point [°C]	−98	−13	−5	−114	0
Boiling Point [°C]	65	198	278	80	100
Flash Point [°C]	12	111	165	12	-
Vapor Pressure 20 °C [kPa]	13.02	0.008	0.00002	5.7	2.33

1.6. Partition of THI into Hydrocarbon Phase

MEG has a lower vapour pressure so it is considered safer. Another consideration undertaken is the high volatility of methanol. Some of it gets lost to the hydrocarbon phase, where it has no use. The amount of methanol or MEG lost to the hydrocarbon phase can be obtained using the equations for distribution constants. However, the amount of MEG lost to gas phase is almost negligible [18].

The distribution constant of methanol in the gas follows;

$$K^{v}_{MeOH} = e^{5.706-5738*[1/T(R)]} \tag{2}$$

The distribution constant of methanol or MEG in the condensate follows;

$$K^{L}_{MeOH} = e^{5.90-5404.5*[1/T(R)]} \tag{3}$$

$$K^{L}_{MEG} = e^{4.20-7.2664*[1/T(R)]} \tag{4}$$

1.7. Justification

Considering the harsh environment, there are some events that may occur. The low temperatures may cause gelling of the injection fluids, incompatible fluids can react and inflict damage on the injection system or become more viscous, causing extra work to the pumping system. In this research, we want to have a fluid that is easier to move downhole.

A particularity of these treatments is that the quantity of THI injected is directly related to how much water is being produced, and also to the decrease of the temperature needed to avoid the hydrate formation zones. As the hydrates form in the aqueous phase, MEG has an advantage over methanol as it can be used, cleaned and re-injected. To its advantage, methanol has a better efficiency dissolving hydrates but is more contaminant and hazardous. Ethanol, considering the production and availability in Brazil, is being used as THI as well.

Others have tested mixtures of MEG and methanol, showing that changing properties of the fluid, like the density and viscosity, cause improvement on the injection process and also on the efficiency dissolving hydrates. Aminaji et al. showed that the mixture of MEG and methanol presented a higher hydrate dissociation rate than that of MEG or methanol alone [19].

Considering these, we believe that a mixture of ethanol and MEG is a good idea. To support the advantages of the mixture on the injection process, we performed experimental tests to study the rheological properties of the mixture. The viscosity of the THI under different conditions of concentration, temperature, shear rate, shear stress was measured. These results would let us know how the fluids being injected would behave, considering changing temperature of the sea during the injection process and how the fluid would behave when changes on the pressure of the production line would cause different flow rates to be used for the injection of THI.

2. Materials and Methods

Characteristics of the THI are shown in Table 3.

2.1. Experimental Tests

Initially, a 50 wt% MEG and 50 wt% ethanol stock solution was made. Later, we made different solutions for MEG/Ethanol mixture using the stock solution and adding distilled water at room temperature until the desired concentration was achieved, as shown in Table 4. Each final solution was agitated to assure they were homogeneous. The solutions were stored and taken to be analyzed.

An Anton Paar rheometer was used to see how the concentration of the THI would change the viscosity of the injection fluid. The rheometer is able to control shear rate, temperature and pressure. A configuration of concentric cylinders was used in the rheometer to measure the viscosity of the solutions. Initially, the solution would be taken to the lowest temperature where the measures of viscosity would start until reaching the highest temperature. At the same time, the shear rate would be changing. All these changes were controlled using control settings on the rheometer software. All the viscosity measurements at a given shear rate and temperature were obtained.

The range of temperatures and shear rates considered for the experimental tests that were performed are shown in Table 4. Some of the variables included a range of temperature from 4–60 °C, shear rate from 1–1000 1/s and fluid concentration from 5–75% weight. It has to be stated that the concentration refers to the quantity of the MEG/EtOH mixture mixed with distilled water. With the results, we would be able to analyze the changes in the viscosity of the solutions.

Table 4. Experimental tests for the dynamic viscosity of the MEG/EtOH mixture.

Condition	Values					
Temperature [°C]	0–60					
Shear Rate [1/s]	1–1000					
%MEG/EtOH	5	15	25	35	50	75

The effect of shear rate can be related to the effect of the flow velocity. The rheometer is used to measure the response of a liquid to an applied force, in this case, the shear stress. The shear stress corresponds to the force applied by the rheometer to deform the fluid.

2.2. Cost Comparison of the Most Used THI

The data used for the economic model was obtained from Kim [10]. In the document, a detailed analysis of the reservoir fluids and simulation of the quantity of methanol and MEG necessary to inhibit hydrate formation can be found [10]. In the modelled case, the MEG injected was assumed to have a concentration of 90% weight, consistent with regenerated MEG generally used in these treatments [20,21].

In this study, we used the NPC for different chemical treatments as the economic comparative parameter. The cost of methanol was based on the quantity needed for the treatment [10]. Meanwhile, for the cost of the MEG, it was necessary to consider the regeneration process that occurs after each injection [10]. In short, all methanol would be spent but not all the MEG would. Only a small percentage of it would be considered as a margin for losses [10]. In the case of ethanol, the costs were based on the quantity of ethanol that would cause the same decrease on temperature as a quantity of methanol. Using Equation (1) we were able to approximate that 30% ethanol could cause a similar effect as 20% methanol. This information was used to simulate and compare the cost of a methanol treatment with the cost of ethanol treatment. This method was used to approximate the quantity of ethanol, as there is not enough data for ethanol to use with common software to determine the quantity of THI needed. To determine the cost of the MEG/EtOH mixture, the quantity of MEG in the mixture, the MEG regeneration and the quantity of ethanol in the mixture was considered. Even though the ethanol could be distilled from the water, this process is yet to be considered. We used a MEG, methanol and ethanol price of 900, 400 and 360 USD/MTon, respectively.

3. Results and Discussion

Table 5 shows a representation of the results we obtained in this research. Considering the volume of the results, only the results for a single temperature and a single shear rate with changing concentration of MEG/EtOH mixture are being presented. The other results are shown in Figure A1 on Appendix A .

Table 5. Tests results for the dynamic viscosity of the MEG/EtOH Mixture − Shear rate = 100 [1/s].

Dynamic Viscosity of the MEG/EtOH Mixture [mPa*s] − Shear Rate = 100 [1/s].															
%MEG/EtOH	Temperature [°C]														
	0	2	4	5	10	15	20	25	30	35	40	45	50	55	60
5	2.53	2.37	2.23	2.16	1.87	1.65	1.47	1.32	1.19	1.10	1.15	1.10	1.06	1.04	1.00
15	3.73	3.46	3.20	3.09	2.61	2.23	1.94	1.71	1.52	1.36	1.23	1.13	1.10	1.10	1.10
25	5.06	4.65	4.28	4.10	3.40	2.86	2.44	2.11	1.85	1.63	1.46	1.32	1.19	1.10	1.09
35	6.64	6.08	5.56	5.32	4.34	3.60	3.03	2.59	2.24	1.97	1.75	1.56	1.41	1.28	1.17
50	8.39	7.68	7.03	6.72	5.49	4.54	3.81	3.25	2.80	2.44	2.15	1.91	1.71	1.54	1.40
75	9.44	8.73	8.06	7.75	6.46	5.43	4.62	3.98	3.46	3.03	2.67	2.38	2.14	1.93	1.76

3.1. Viscosity of THI as Function of the Temperature of the Fluid

In Figure 4 we can see both effects. First the temperature effect: it is evident in this case that the temperature plays an important role in the viscosity of the injection fluid, as this property shows a decreasing tendency when the temperature is increasing. In this way the higher the temperature is, the lower the viscosity of the injection fluid is. Considering that the average temperature of the seawater is near 4 °C, it means that the closer we get to the bottom of the sea, the more viscous the fluid will be, increasing the drag force between the pipeline surface and the fluid boundary layer, making its transport more difficult, traducing this effect on the need of a more powerful pumping system as much deeper as the injection fluid gets.

In Figure 4 it is possible to see a hint of the concentration-effect: the higher the concentration, the higher the viscosity. We can also see that the viscosity of the mixture of MEG/EtOH is lower than the viscosity of pure MEG. The data series Blank corresponds to pure MEG viscosity tendency, adapted from Yua et al. [22].

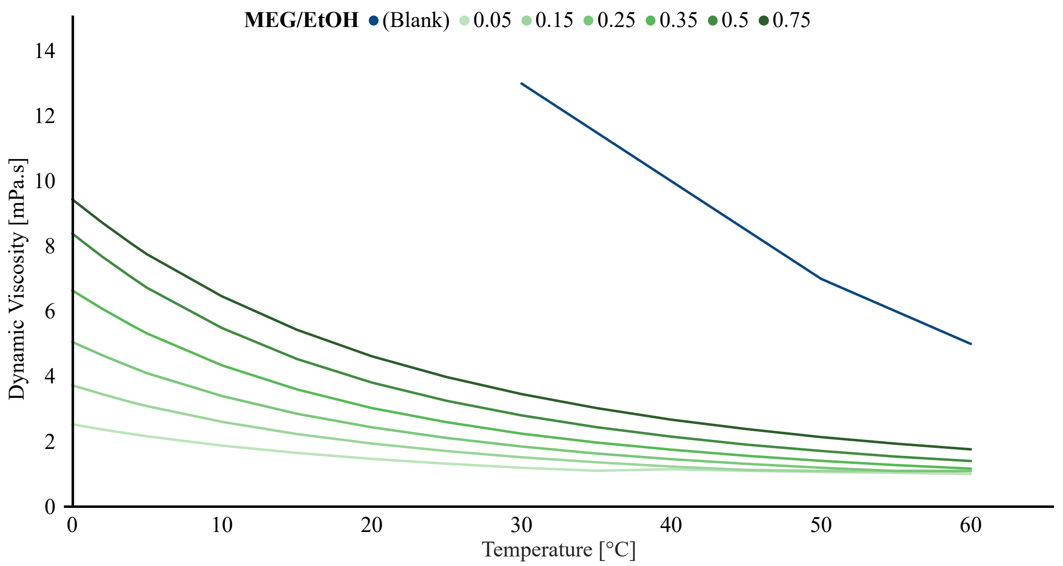

Figure 4. Comparison between the dynamic viscosity of the MEG/EtOH mixture as function of temperature for different %MEG/EtOH using a shear rate of 100 1/s and the dynamic viscosity of a pure MEG solution (Blank).

3.2. *Viscosity of THI as Function of the Concentration of MEG/EtOH Mixture in the Fluid*

In Figure 5 it is easier to see the concentration effect. It is valid to say that for the 25% MEG/EtOH, the remaining 75% is distilled water, with a similar relation for the other solutions. As it can be seen in Figure 5, the concentration of the fluid has a thickening effect: the higher the concentration, the higher the viscosity. It can be said that working with thicker or more viscous fluids, more power is needed for the pumping system. That is why it is important to have a THI with as low a viscosity as possible, without compromising the effectiveness as a gas hydrate inhibitor.

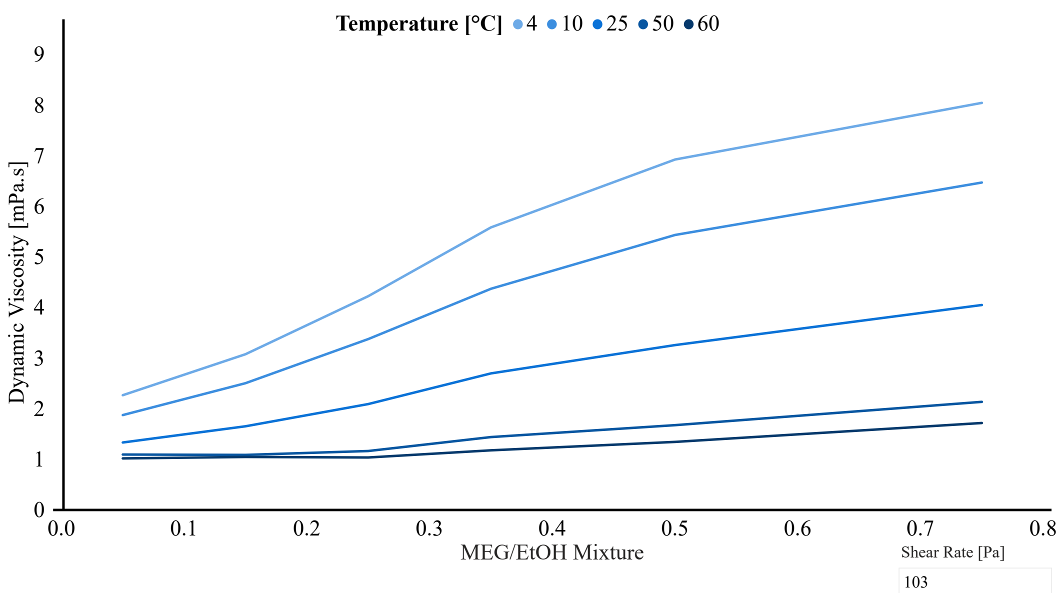

Figure 5. Dynamic viscosity of the MEG/EtOH mixture as function of %MEG/EtOH for different temperatures using a shear rate of 103 1/s.

Paulo et al. [23], presented results considering the effect of the changing viscosity on the injection process. They used the pressure drop within a vertical column to analyze which of them would need a more powerful pressure system. Some of their conclusions were that pure MEG would need the higher injection pressure coming from the pressure system, followed by the MEG/EtOH mixture and then the pure alcohols [23]. Of course, considerations such as safety, hazard and even green chemistry need to be taken into account to make the best choice.

3.3. Viscosity of THI as Function of the Shear Rate

In Figure 6, we can see the effect of the shear effect. Increasing shear rate effect can be similar to increasing flow velocity effect. The shear rate is related to the drag effect that the solid-fluid interaction between the pipeline surface and the boundary layer of the liquid has. We can see a near-Newtonian fluid behaviour as the viscosity of the fluid is almost constant for increasing shear rate. There is more near-constant viscosity, meaning that at low flow velocities or low shear rate the fluid is almost Newtonian. On the section where the viscosity increases, the effect can be called shear thickening proper of dilatant fluids. To the extent of this research, the effect of Newtonian or No-Newtonian behaviour will not be discussed. We are working towards more substantive results on this matter.

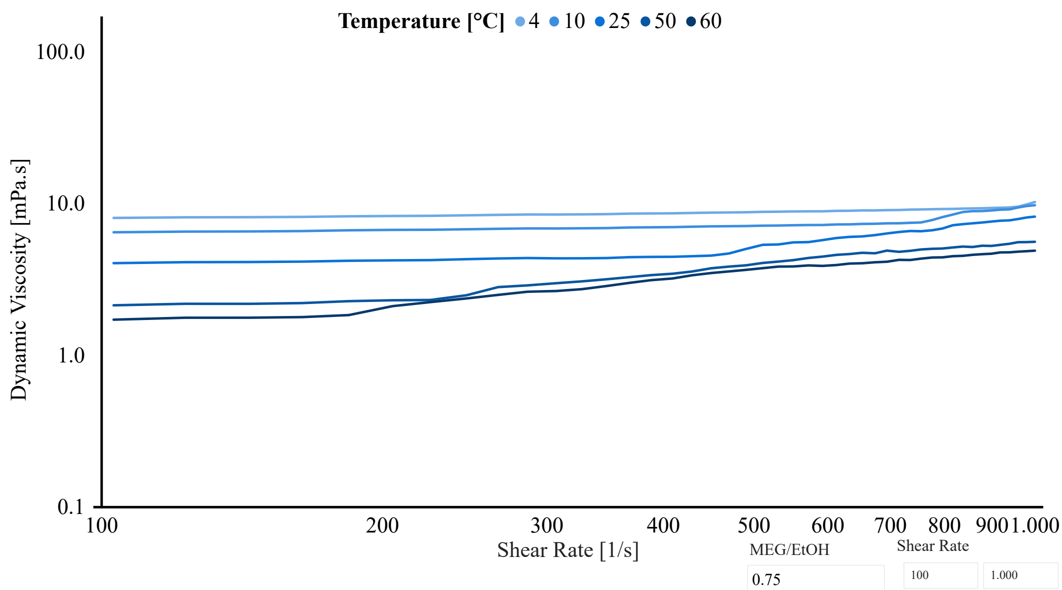

Figure 6. Dynamic viscosity of the MEG/EtOH mixture as function of shear rate for different temperatures, 75%MEG/EtOH solution.

In the case of Figure 6, the results correspond to the 75% MEG/EtOH mixture. It is evident how temperature plays an important role in the rheology of the fluid. For high temperatures, as much as 50 or 60 °C, the shear-thickening effect is more notorious than for low temperatures as 4 or 10 °C. For these temperatures, it seems like the shear-thickening effect is more important when dealing with high shear rates, which can be related to high flow rates or high pressures.

3.4. Shear Stress and Shear Rate Effect

In Figure 7 we can see how the shear stress is directly proportional to shear rate. This is consistent with Newtonian fluids and sometimes for dilatant fluids as well.

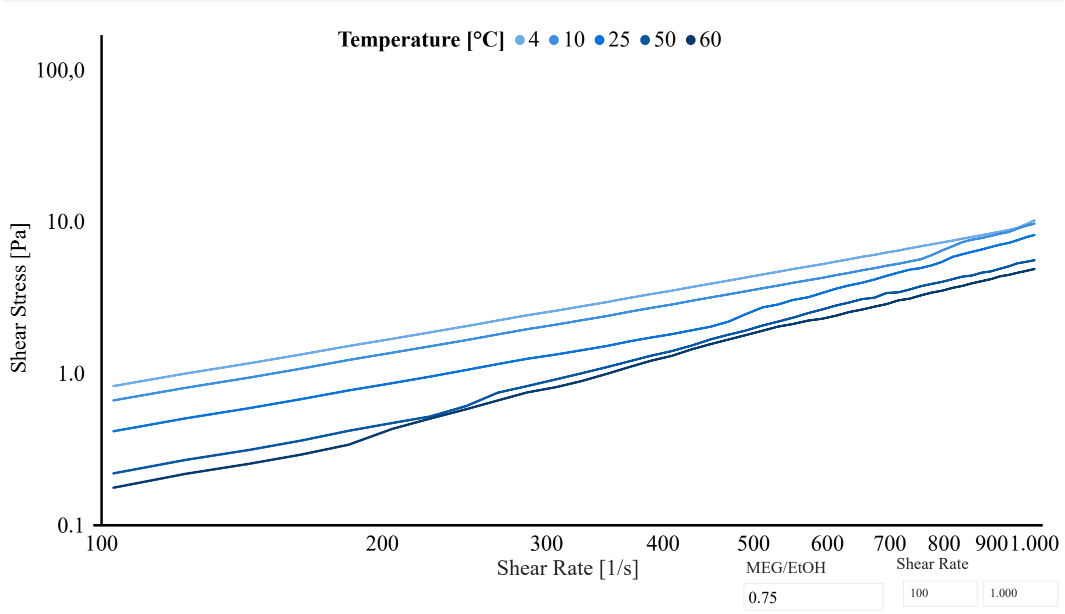

Figure 7. Shear stress Vs. Shear rate for different temperatures for a 75% MEG/EtOH.

It seems like the temperature of the fluid has a larger effect on the shear-thickening behaviour of the fluid. In this case, the results correspond to the 75% MEG/EtOH mixture, and shear rate between 100–1000 1/s. For other concentrations or shear rate please go to the supporting documents section. Considering the proportional relation between shear stress and shear rate for 4 °C, it seems like the behaviour of the fluid is Newtonian for low temperatures. This is convenient taking into account the average temperature of the ocean, around 4 °C, making the temperature of the injected fluid around 4 °C too.

3.5. Cost Comparison

Although the MEG injected could be regenerated, this cost is one of the biggest drawbacks when using MEG, making the MEG system costs higher than those of a methanol injection system. This is the case for the ethanol and MEG/EtOH system as well. Higher capital investment and more expensive MEG cost make the other systems more economical than MEG system based on an annual injection. In this case, the most cost-effective treatment in increasing order is methanol, ethanol, MEG/EtOH and MEG, as can be seen in Figure 8.

From Figure 8, it can be seen that the pure MEG and the MEG/EtOH treatment rendezvous when the number of injections per year is more than 2.9 times per year. From this moment, pure MEG treatment starts to become more economical.

When the injection frequency per year increases, it is evident that the operational costs increased too. This effect seems to be more important for the injection of methanol and ethanol treatments rather than for the MEG treatment. For methanol and ethanol, the increase in the cost is proportional to the increase of the injection frequency. One of the reasons for this behaviour is the possibility to regenerate MEG on the topside.

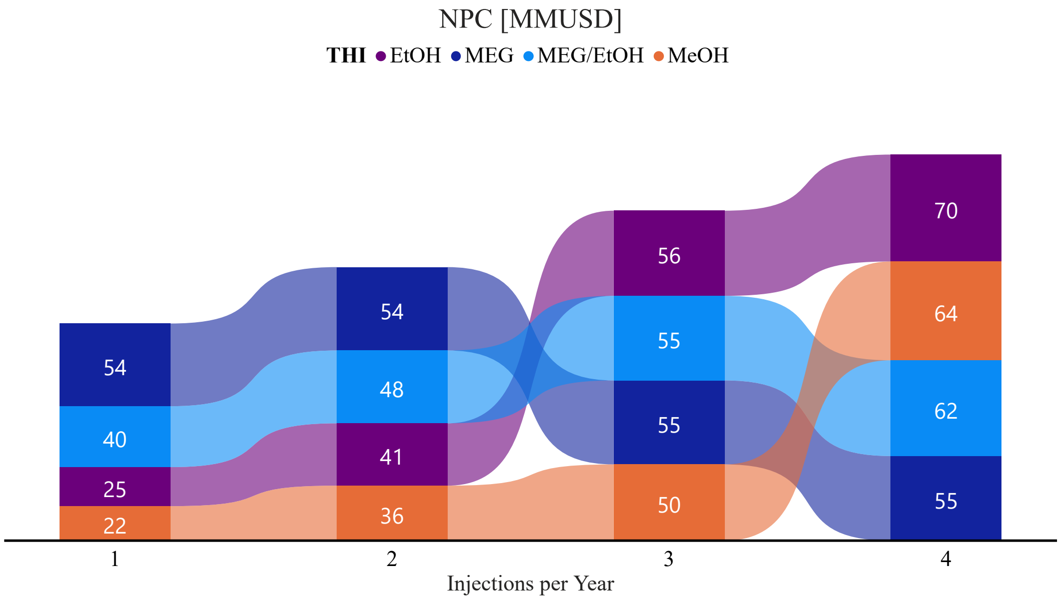

Figure 8. Net present cost for each THI as function of frequency of injections per year.

The increase of the MEG treatment is slower as the regeneration process helps with the operational costs. As less MEG is needed to be purchased every year, it was considered a small margin of losses which is evident in a small increase in the cost. This characteristic made pure MEG treatment more convenient for others. In the case of the treatment using the MEG/EtOH mixture, this effect seems only important for high frequency per year injection treatments, as its cost is almost always lower than the pure MEG treatment cost. In Figure 9 it can be seen as a comparison for each THI and how the cost would increase taking into consideration the number of injection treatments per year.

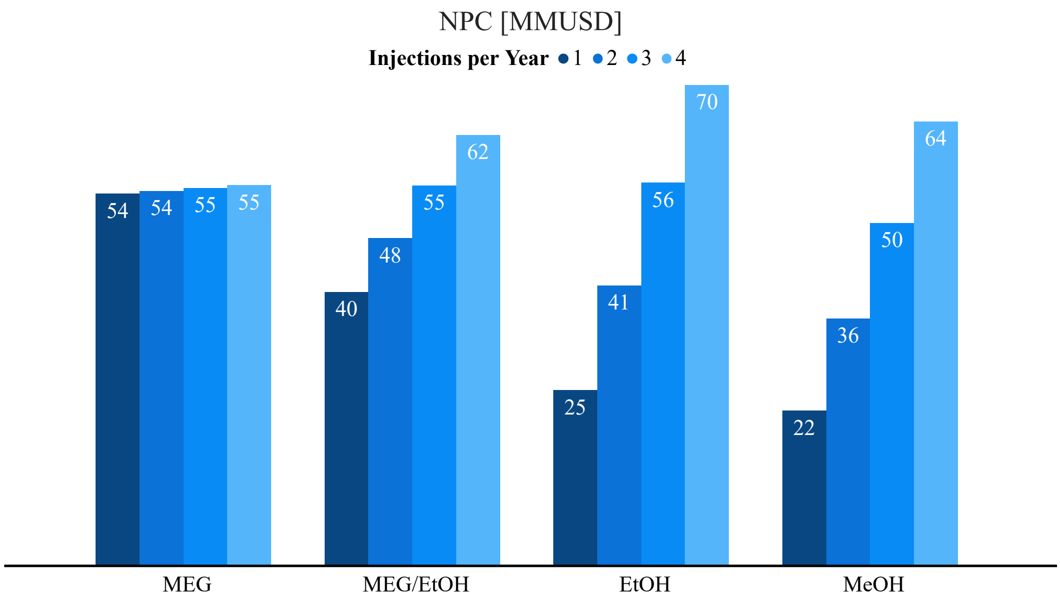

Figure 9. Net present cost Vs Injections per year.

On the question of choosing between MEG or MEG/EtOH mixture as a hydrate inhibitor, it is necessary to consider not only the cost but also the effect of the viscosity and density of the fluids, as they would translate to lower needs of power coming from topside.

Pure MEG injection offered advantages, considering MEG can be regenerated. On the other hand, when a small number of injections is required, the best option would be ethanol or MEG/EtOH mixture.

Setting aside the low cost, safety concerns, and hazardous characteristics of methanol, another issue with the use of methanol is that when it evaporates into the hydrocarbon phase, it could cause problems in the processing units. Also, depending on the quantity of methanol in the hydrocarbon phase, this could cause penalties on the sale price. For instance, methanol concentration higher than 50 ppm could lead to an oil price reduction between 2–4 USD/MTon and most of the refineries cannot operate with it if the methanol concentration is over 200 ppm [10]. For these cases, there is a need for a pre-treatment to remove the methanol which would induce higher operative costs. In the case of MEG, it does not affect the price of the production from the oil field [24].

4. Conclusions

The conclusions for this research are as follows:

- This work compared the economic feasibility of the use of methanol and MEG with others, such as ethanol and MEG/EtOH mixture, based on the mixture injection in terms of injection frequency and inhibitor amount when hydrate inhibitor is injected intermittently for preventing hydrate in sub-sea flowlines.
- Considering the shear-thickening effect, we can say that having a low shear rate or low flow velocity is more convenient as the fluid behaves as a Newtonian fluid and the force against its movement is lower. This effect needs to be considered when designing the pumping system.
- The viscosity of the mixture of MEG/EtOH is lower than the viscosity of the MEG alone. As the viscosity is lower, it would be easier to pump the mixture downhole than MEG alone.
- Even though increasing the concentration increases the viscosity, the higher concentration of 75% mixture of MEG/EtOH has a much lower viscosity than pure MEG.
- Based on the economic analysis, the MEG/EtOH mixture shows good results when compared with pure MEG treatments. The frequency and quantity of THI needed have to be analysed.
- The loss of MEG/EtOH to the vapour phase would be reduced when compared to pure methanol. When using MEG/EtOH mixture, we assumed the loss of MEG would be negligible. The loss of EtOH would be less than the loss of pure MeOH, as the quantity of EtOH in solution is quite smaller to that of a pure MeOH treatment.
- To make the best decision it is important to take into consideration the fluid dynamics and rheology effects of the fluid, as having a lower viscosity is better. On this front, the MEG/EtOH presents good advantages compared to the MEG. To its advantage, the MEG used in the treatments can be regenerated. At some point, there is a need for a trade-off between a better injection process based on fluid effects and the price effect lead by MEG.
- With the advantage of injection, the next step is to prove its efficiency as a THI in a batch system.

Author Contributions: Conceptualization, P.P. and T.A.N.; methodology, P.P.; software, P.P.; validation, P.P.; formal analysis, P.P.; investigation, P.P.; resources, T.A.N.; data curation, P.P.; writing—original draft preparation, P.P.; writing—review and editing, P.P. and T.A.N.; visualization, P.P.; supervision, T.A.N.; project administration, T.A.N.; funding acquisition, T.A.N. All authors have read and agreed to the published version of the manuscript.

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

Abbreviations

The following abbreviations are used in this manuscript:

MEG	Mono Ethylene Glycol
TEG	Triethylene Glycol
MeOH	Methanol
EtOH	Ethanol
CO_2	Carbon Dioxide
THI	Thermodynamic Hydrate Inhibitors
PLEMs	Pipeline End Manifold
PLETs	Pipeline End Termination
ILTs	In-Line Tee
NPC	Net Present Cost
NPV	Net Present Value
TCF	Trillion Cubic Feet

Appendix A

Appendix A.1. Dynamic Viscosity of the MEG/EtOH Mixture as Function of Shear Rate for Different Temperatures

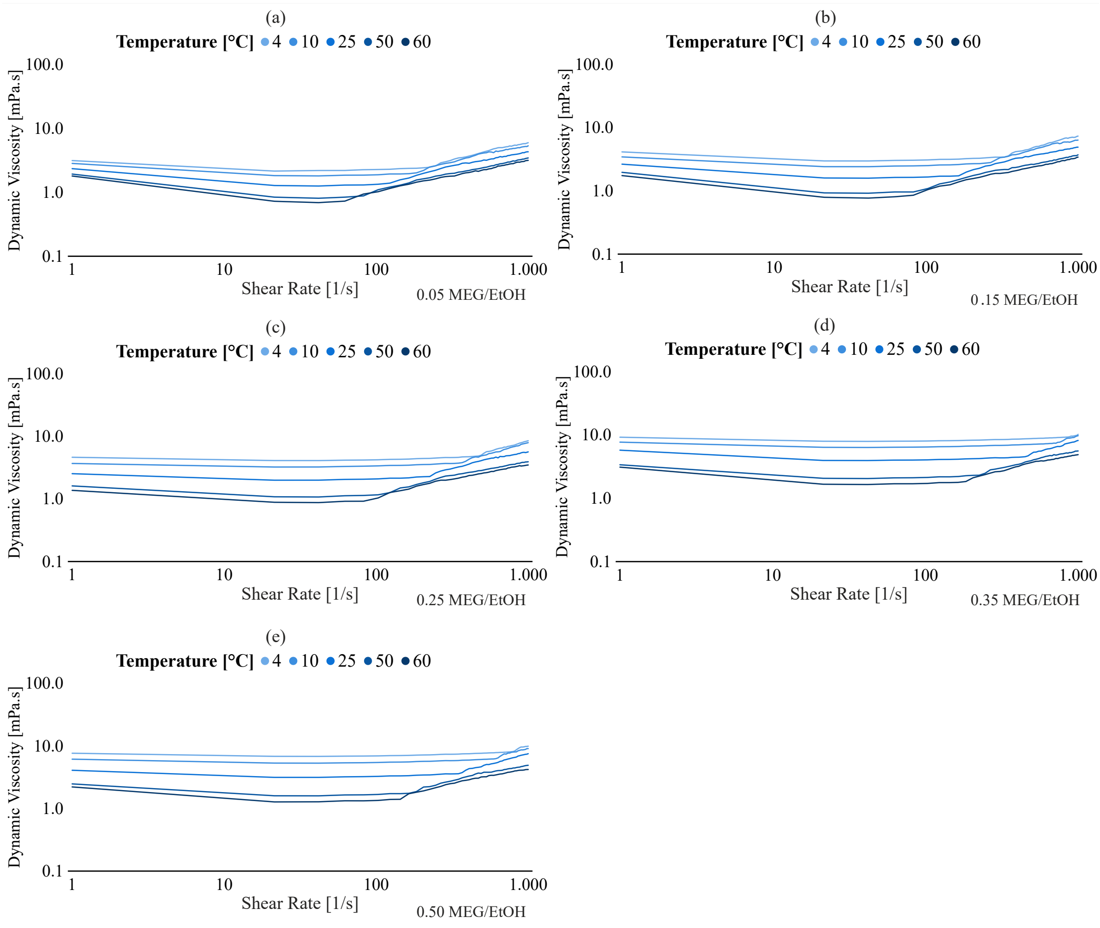

Figure A1. Dynamic viscosity of the MEG/EtOH mixture as function of shear rate for different temperatures, (**a**) 5%MEG/EtOH, (**b**) 15%MEG/EtOH, (**c**) 25%MEG/EtOH, (**d**) 35%MEG/EtOH, (**e**) 50%MEG/EtOH.

Appendix A.2. Hydrates Curves Using Equation (1)

Table A1. Data used in Figure 2.

P [bar]	T [°C]	20% MeOH	20% MEG	20% EtOH
11	3	1.54	2.13	1.98
13	4	2.54	3.13	2.98
15	5	3.54	4.13	3.98
17	6	4.54	5.13	4.98
20	7	5.54	6.13	5.98
23	8	6.54	7.13	6.98
27	9	7.54	8.13	7.98
32	10	8.54	9.13	8.98
36	11	9.54	10.13	9.98
41.5	12	10.54	11.13	10.98
48	13	11.54	12.13	11.98
56	14	12.54	13.13	12.98
66	15	13.54	14.13	13.98
77	16	14.54	15.13	14.98
89	17	15.54	16.13	15.98
105	18	16.54	17.13	16.98
109	18.2	16.74	17.33	17.18
113	18.4	16.94	17.53	17.38
117	18.6	17.14	17.73	17.58
121	18.8	17.34	17.93	17.78
125	18.9	17.44	18.03	17.88
140	19	17.54	18.13	17.98
160	19.4	17.94	18.53	18.38

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A State-Dependent Constitutive Model for Gas Hydrate-Bearing Sediments Considering Cementing Effect

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Abstract: This paper presents a state-dependent constitutive model for gas hydrate-bearing sediments (GHBS), considering the cementing effect for simulating the stress–strain behavior of GHBS. In this work, to consider the influence of hydrate on matrix samples in theory, some representative GHBS laboratory tests were analyzed, and it was found that GHBS has obvious state-related characteristics. At the same time, it was found that GHBS has high bonding strength. In order to describe these characteristics of GHBS, the cementation strength related to hydrate saturation is introduced in the framework of a sand state correlation model. In addition, in order to accurately reflect the influence of cementation on the hardening law of GHBS, the degradation rate of cementation strength is introduced, and the mixed hardening theory is adopted to establish the constitutive model. The model presented in this paper reproduces the experimental results of Masui et al. and Miyazaki et al., and the prediction performance of the model is satisfactory, which proves the rationality of this work.

Keywords: marine geology; gas hydrate-bearing sediments; state parameter; cementation; mixed hardening; constitutive model

1. Introduction

With the continuous development and progress of exploration technology and equipment, the exploitation of oil and gas resources has gradually shifted from land and shallow sea to deep sea [1]. There are abundant resources in the ocean, especially natural gas hydrate, which can reach twice the total amount of traditional fossil fuels [2]. Gas hydrates are considered as one of the most promising strategic resources for commercial development in the future [3].

Gas hydrates are caged crystalline compounds formed by water and natural gas under certain temperature and pressure conditions. They are widely distributed in seabed strata and have the advantages of being clean, with large reserves and high heat value [3]. Some countries have carried out on-site exploitation of hydrate, and Mallik in Canada was the first place to carry out gas hydrate test mining [4]. Gas hydrate test mining was carried out three times, in 1998, 2002, and 2007–2008, respectively, and the production response characteristics of gas hydrate-bearing sediments (GHBS) were directly identified for the first time. However, due to the limitations of the production test cycle, this study is not enough to fully evaluate the resource potential of gas hydrate. In 2012, American researchers conducted the world's first hydrate production test project combining the carbon dioxide replacement method and depressurization method on the northern slope of Alaska, and it confirmed the feasibility of developing hydrate by using the replacement method on the technical level [5]. Since 2000, Japan has carried out the world's first sea area hydrate test production in Nankai

Trough, and the second test production was carried out in this area from May to June, 2017 [6]. However, the long-term production feasibility of the existing technology cannot be confirmed by the current gas production time. In May 2017 and February 2020, China successfully carried out gas hydrate test production [3]. Generally speaking, the exploitation of gas hydrates still faces great challenges. At present, the common mining technologies mainly include the depressurization mining method [7], thermal stimulation method [8], CO_2 replacement mining method [9] and a combination of several mining methods [7]. In addition to these mining technologies, there are mainly horizontal wells and vertical wells in a wellbore layout, among which horizontal wells are considered as the most feasible commercial mining method.

Geological survey data show that the cementation of gas hydrate significantly improves the strength of marine sediments [10]. However, the formation and decomposition of gas hydrate are affected by temperature, pressure, gas type and seawater salinity [11]. When these conditions change, the occurrence state of gas hydrate will also change. Under unfavorable conditions, hydrate will decompose to produce a large amount of natural gas. With the decomposition of gas hydrate, the void ratio of GHBS increases and becomes loose sand, while the cementation of soil particles weakens and the strength of soil decreases [12]. On the other hand, a large amount of free gas is released by dissociation, which leads to a rapid increase in pore pressure in GHBS, a decrease in effective stress of soil, static liquefaction of the submarine slope and submarine landslide [13]. Therefore, studying and analyzing the strength and deformation of GHBS, and expressing their mechanism and general rules in an appropriate constitutive model for application to theoretical analysis and for handling practical engineering problems, have gained importance in the task of guaranteeing the safe exploitation of hydrates.

On the basis of mastering the mechanical properties of GHBS, it is an important issue to carry out numerical simulation of the submarine slope [14]. Combined with the mechanical properties of GHBS, which are similar to sand or special soil, based on different model frameworks, several types of constitutional models have been proposed. Yu et al. [15] and Yan et al. [16] put forward a modified nonlinear elastic model of GHBS under the framework of the Duncan–Chang model, considering the influence of hydrate saturations (S_h), but the model cannot describe the softening behavior of GHBS. Sultan et al. [17] put forward an elastoplastic model based on the modified Cambridge model, which can consider strain softening and dilatancy. However, due to the adoption of the associated flow rule, the calculation of volume deformation is not ideal. Yan et al. [18] referred to the mathematical model of cemented soil, regarded GHBS as composite cemented material, introduced additional internal variables to describe the effect of hydrates on the yield strength and established a constitutive model of GHBS. The model suggests that the cementation has different decline rates before and after the peak value, which has not been effectively confirmed by experiments. Klar et al. [19] established an ideal elastoplastic model based on the Mohr–Coulomb strength criterion. Although its parameters are few, strain softening and dilatancy cannot be considered. So far, there have been few constitutive models for the state dependent properties of GHBS, and almost all the established models adopt isotropic hardening theory, which can not fully reflect the mechanical properties of GHBS.

To sum up, the hydrate exploitation activities that have been carried out now are facing many challenges. In order to exploit natural gas hydrate safely, scholars have conducted a profound study on the mechanical behavior of energy soil from both qualitative and quantitative perspectives. In this study, combined with the state-related characteristics of GHBS, under the framework of the state-related model of sand, the cementation strength of GHBS is introduced, the evolution law of cementation strength is established, and the state-related constitutive model of GHBS is established by adopting the mixed hardening theory.

2. State-Related Characteristics of GHBS

Many scholars have conducted indoor experiments on GHBS. Winters et al. [20] and Hyodo et al. [21] synthesized samples and studied the effects of initial void ratio and hydrate saturation on the stress–strain behavior of GHBS. Masui et al. [22] prepared two types of GHBS using percolated methane gas in a specimen of Toyoura sand mixed with powder ice and excessive water and later carried out a series of triaxial tests with different effective confining pressures. Yun et al. [23], Miyazaki et al. [24], Ghiassian et al. [25], Liu et al. [26], Madhusudhan et al. [27] and Dong et al. [28] conducted experimental studies on GHBS.

On the basis of existing research results, Soga et al. [29] have described the mechanical properties of GHBS in detail, but because the mechanical properties of GHBS are the basis of this study, in order to facilitate understanding, this paper briefly introduces the main mechanical properties of hydrate sediments:

(1) GHBS may show strain hardening or softening during shearing, and its characteristics depend on S_h, compactness and stress level.
(2) For the deformation characteristics of GHBS, shear shrinkage and dilatancy may occur, which are mainly related to internal states, such as hydrate occurrence mode and S_h.
(3) The cementation of GHBS has an important influence on its characteristics of strength and deformation. With the decline of cementation, it often shows a more obvious phenomenon of softening and dilatancy.

To sum up, the strength characteristics of GHBS not only depend on the void ratio and stress level, making it similar to sand, but are also related to S_h and cementation, thus producing essential differences in the mechanical properties of the ordinary soil and sand. Therefore, GHBS is also a kind of state-dependent material. By constructing appropriate expressions of the state parameter, the state-dependent characteristics of GHBS can be described.

3. State-Dependent Elastoplastic Constitutive Model of GHBS

3.1. Yield Function

Since GHBS exhibits characteristics similar to sand, the yield function of the sand model is modified. A large number of studies on sand have shown that the deformation caused by consolidation is very small, while the deformation of sand is mainly caused by stress ratio [30–32]. Poorooshasb et al. [33] assumed that the yield trajectory of sand is a series of straight lines with a constant stress ratio. In Figure 1, the schematic diagram of the yield surface shows the shape of the yield surface, which is represented by Equation (1).

$$f = q^* - M^* p^* \quad (1)$$

where q^*, and p^* are the mean normal stress and generalized shear stress of sand, respectively, and M^* is the stress ratio of critical state.

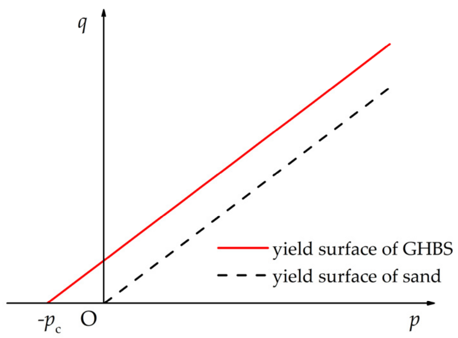

Figure 1. Schematic diagram of the yield surface.

Considering that the cementation of GHBS has an important influence on the yield strength, the straight line represented by Equation (1) is translated to the left to establish the yield function of GHBS, as shown by Equation (2), whereas the shape of the yield surface is shown in Figure 1. If the attenuation of cementation is considered, the subsequent yield surface of GHBS will simultaneously move to the right with the loading process.

$$f = q - M(p + p_c) \quad (2)$$

where q and p are the mean normal stress and generalized shear stress of the GHBS, respectively, p_c is the cementation of GHBS, and M is the critical state stress ratio, which is equal to M^*.

When the stress ratio reaches M, GHBS enters the state of destruction. The stress ratio η is given by Equation (3).

$$\eta = q/(p + p_c) \quad (3)$$

3.2. Cementation

Referring to Sanchez's and Uchida's method for determining the cementation of GHBS [14,34], it is assumed that the initial value of cementation p_{c0} satisfies the exponential relationship with S_h (see Equation (4)).

$$p_{c0} = \alpha S_h^{\beta} \quad (4)$$

where α and β are the model parameters, while all other terms have the same meaning as defined previously.

Compared with ordinary sand, shear behavior not only causes rotation, slip and redistribution of particles in the material, but it also causes hydrate breakage and debonding between the hydrate and sand particles [35]. With the development of strain, cementation will decline. This difference directly affects the macroscopic mechanical behavior of GHBS. In research on the evolutionary pattern of cementation of GHBS, several authors [14,18,34] assume that it is a function of plastic shear strain (ε_s^p) and have obtained ideal prediction effect. In this paper, the same assumption is made, and it is found that ε_s^p cannot be recovered. The evolutionary pattern of cementation of GHBS is expressed using Equation (5).

$$dp_c = -a_c p_{c0}\, d\varepsilon_s^p \quad (5)$$

where a_c indicates the attenuation rate of the cementation of GHBS.

3.3. State Parameters and Dilatancy

The dilatancy of GHBS depends on the internal state and stress level, which can be reflected by the yield function. Therefore, it is necessary to construct a state parameter expression that reflects the internal state and then to clarify the dilatancy of GHBS by describing the current state.

If e is the current void ratio of the material, and e_c is the critical void ratio, then the state parameter φ can be expressed as the difference [36] and the ratio [37] between e and e_c. Yao et al. [32] use the void ratio e_η corresponding to the mean normal stress p under the condition of equal stress ratio to replace e_c and construct the state parameter φ considering the stress ratio. In this paper, the state parameter φ is expressed using Equation (6).

$$\varphi = e/e_c \quad (6)$$

According to the basic theory of soil mechanics, the relationship between the current void ratio e of GHBS, the initial void ratio e_0 and the volume strain ε_v is given by Equation (7).

$$e = e_0 - (1 + e_0)\varepsilon_v \quad (7)$$

In order to obtain the expression of the state parameter φ of the GHBS, it is necessary to establish the expression of the initial void ratio e_0 and the critical void ratio e_c. The hydrate has the effects of filling and cementation on GHBS. Furthermore, for the GHBS mainly filled with the filling effect, e_0 may decrease with the increase of S_h; however, for the GHBS-containing structure, the larger the S_h, the smaller is the e_0. The influence of the content and occurrence mode of hydrate on e_0 is not completely clear at present. Additionally, the samples of GHBS prepared indoors are affected by methane gas scouring, which may lead to uneven samples. Therefore, it is difficult to establish the mathematical relationship between e_0 and S_h. In order to reduce the model parameters, this paper assumes that e_0 and S_h of GHBS satisfy a simple inverse proportional relationship, as given by Equation (8).

$$e_0 = e_0^* - \frac{kS_h}{1 + S_h} \tag{8}$$

where e_0^* is the initial void ratio of the host sand, and k is the model parameter that reflects the influence of hydrate occurrence mode and formation conditions on the initial void ratio of GHBS.

Yoneda et al. [38] verified that the deformation process affects the occurrence conditions of hydrate and leads to hydrate decomposition, whereas the consolidation line of GHBS gradually approaches the consolidation line of the host sand, due to which the GHBS should have the same critical state line (CSL) as the host sand. The CSL of sand can be expressed using Equation (9).

$$e_c = e_{c0} - \lambda (p/p_a)^{\xi} \tag{9}$$

where e_{c0} is the void ratio of CSL when p = 1kPa, λ is the slope of CSL in e-ln$p$ space, ξ is the material parameter with the generally accepted value of 0.7 for sand, and p_a is the atmospheric pressure (101kPa) introduced for dimensional unification.

Using the expression of dilatancy equation proposed by Wan and Guo [37], the state parameter φ, as given by Equation (6), is introduced into the dilatancy equation, which is given by Equation (10).

$$d = M\varphi^{\,m} - \eta \tag{10}$$

where m is the model parameter, which can be obtained from the results of the triaxial test. It can be seen that when m = 0, Equation (10) is reduced to the dilatancy equation of the Cambridge model.

3.4. Hardening Modulus

The plastic strain of GHBS can be divided into two parts. One part is related to the expansion of the yield surface. For this part, η is used to reflect the isotropic hardening of GHBS with the evolution of plastic strain. The other part results from the movement of the yield surface. Cementation reflects the motion hardening of GHBS with the evolution of plastic shear strain. Both of them constitute the mixed hardening of GHBS.

The hardening caused by the stress ratio is the same as the hardening modulus expression of sand, while the isotropic hardening modulus A_1 is given by Equation (11).

$$A_1 = hG(M/\eta - \varphi) \tag{11}$$

where h is the model parameter and G is the shear modulus of GHBS.

For sand, the shear modulus has the following empirical correlation (Equation (12)).

$$G^* = G_0^* \frac{(2.97 - e^*)^2}{1 + e^*} \sqrt{pp_a} \tag{12}$$

where G^* is the shear modulus of sand and G_0^* is the model parameter.

Yoneda et al. [38] have given the empirical correlation of the shear modulus of GHBS under 1MPa effective confining pressure, which is given by Equation (13).

$$G = 91.482\,[(1 + e_0)(1 - S_h)]^{-1.363} \tag{13}$$

Based on Equations (12) and (13), the shear modulus of GHBS is rewritten and given by Equation (14).

$$G = (1 - S_{\mathrm{h}})^{-\chi} G_0^* \frac{(2.97 - e)^2}{1 + e} \sqrt{p p_{\mathrm{a}}} \tag{14}$$

where χ is the material parameter of GHBS and reflects the degree of influence of the hydrate on the hardening modulus.

The cementation of GHBS also causes material hardening during shearing, which has the characteristics of kinematic hardening. In this paper, the kinematic hardening modulus is represented by Equation (15).

$$A_2 = -\, a_{\mathrm{c}} \eta p_{\mathrm{c0}} \tag{15}$$

Therefore, the hardening modulus of GHBS can be expressed using Equation (16).

$$A = A_1 + A_2 = hG(M/\eta - \varphi) - a_{\mathrm{c}} \eta p_{\mathrm{c0}} \tag{16}$$

It can be seen that, when $S_{\mathrm{h}} = 0$, and $p_{\mathrm{c0}} = 0$, Equation (16) returns to the hardening modulus expression of sand.

4. Model Verification

4.1. Model Parameters

The model established in this paper contains thirteen parameters and can be divided into two categories, as represented by the parameters given in Tables 1 and 2. Among them, sand material parameters ξ, λ, e_{c0} and μ can be obtained through the isotropic compression test of the host sand, while M, h, m and G_0^* are calibrated according to the results of the triaxial test. The hydrate-related parameters k, α, β and a_{c} are obtained by fitting the triaxial test results of different S_{h} values, whereas χ is calculated using Equation (14).

Table 1. Sand material parameters.

Parameter	Value	Parameter	Value
ξ	0.7	M	1.5
λ	0.0191	h	0.0533
e_{c0}	0.9344	m	3.16
μ	0.3	G_0^*	1944

Table 2. Hydrate-related parameters.

Parameter	Value
k	0.29
α(MPa)	7.75
β	2.90
a_{c}	4.97
χ	0.94

4.2. Model Prediction

Masui et al. [22] took Toyoura sand as the matrix material with an initial void ratio of 0.65, prepared GHBS samples with different S_{h} and conducted triaxial drained tests under the effective confining pressure of 1MPa. The test data of Masui are predicted using the model proposed in the current paper, and the parameters used are presented in Tables 1 and 2.

Figure 2 shows the comparison between experimental and model results for different S_{h} values in terms of deviatoric stress. It can be seen that the predicted results of the model are consistent with the test data, and the model can satisfactorily reflect the strength and strain softening characteristics of GHBS. With the increase in S_h, the stiffness and strength of GHBS gradually increase, and the phenomenon of strain-softening becomes more obvious. The prediction curve of the volume strain of GHBS is shown in Figure 3. Compared to the experimental data, it can be seen that the model can satisfactorily describe the effect of hydrates on dilatancy. When the strain is small, GHBS mainly shows shear shrinkage. With the increase in axial strain, the volume strain gradually increases. Furthermore, higher the value of S_h, more obvious is the dilatancy.

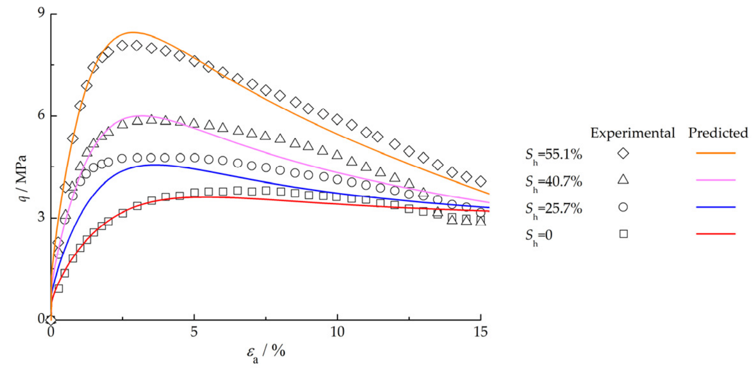

Figure 2. Comparison of the predicted stress–strain curves with the experimental results [22].

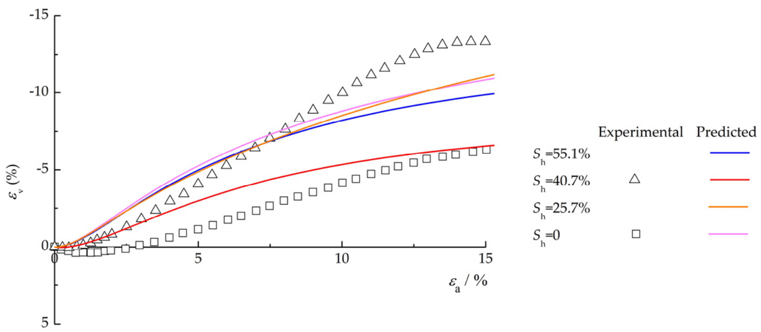

Figure 3. Comparison of the predicted volume strain curves with the experimental results [22].

In order to test the applicability of the model under different effective confining pressures, it is compared with the test data of Miyazaki [24]. Miyazaki et al. also used Toyoura sand and methane to prepare samples with approximately equal S_h values. The initial void ratio of host sand samples is 0.6, while the effective confining pressures are varied consecutively through values of 0.5MPa, 1MPa, 2MPa and 3MPa. During the tests, the axial strain ε_a and radial strain ε_r of GHBS are monitored.

As the test conditions of Miyazaki et al. [24] and Masui et al. [22] are not the same, the model parameters are changed. Table 3 presents the parameters used to predict the test data of Miyazaki et al. The results predicted by the model are compared with the experimental data. It can be seen from Figure 4 that, for the same S_h, the increase in effective confining pressure makes the GHBS change from strain-softening to strain-hardening, because the constraint effect of effective confining pressure improves the rigidity and strength of GHBS. Meanwhile, the rate of decline of cementation of GHBS decreases. Figure 5 shows the comparison between the relationship curve of predicted radial strain and the experimental data. The predicted curve is in good agreement with the experimental data, indicating that the model proposed in the current paper has a very good applicability.

Table 3. Calculation parameters for model prediction.

Parameter	Value	Parameter	Value
G_0^*	2496	β	3.49
k	0.08	a_c	1.95
α(MPa)	7.71	χ	1.08

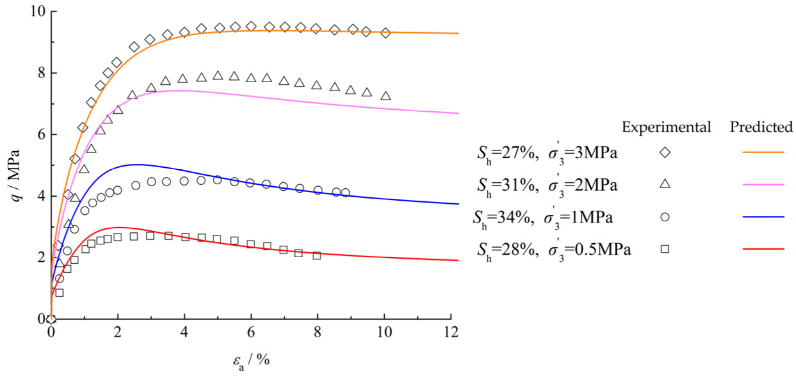

Figure 4. Comparison of the predicted stress–strain curves with the experimental results [24].

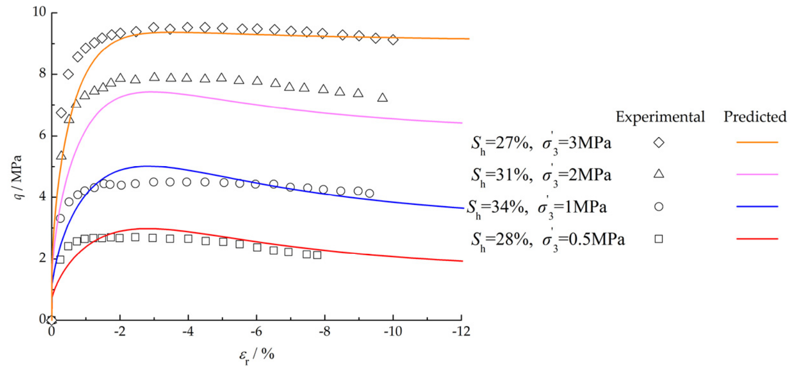

Figure 5. Comparison of the predicted stress–strain curves with the experimental results [24].

5. Conclusions

In this study, an elastoplastic model is proposed based on the framework of the sand state-dependent constitutive model, in which GHBS is considered as a bonded material. The main conclusions are as follows:

(1) By summarizing the test rules of GHBS, it is found that GHBS has certain cohesive strength and obvious state-related characteristics. In this paper, GHBS is regarded as a special cementing material, and the sand state correlation model is selected as the basic framework.
(2) By constructing appropriate state parameter expressions, introducing the cementation and its evolutionary pattern and adopting the mixed hardening rule, the state-dependent constitutive model of GHBS is established.
(3) The comparison between the predicted results using the proposed model and the experimental data shows that the established constitutive model is in good agreement with the experimental data. The model can satisfactorily describe the strain-hardening and strain-softening characteristics of GHBS and can effectively reflect the correlation characteristics of strength and stiffness with hydrate saturation, effective confining pressure and other factors.

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