University of Stavanger

**Faculty of Science and Technology**

# MASTER'S THESIS

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# Abstract

Global climate change is long-term risk related to the accumulation of carbon dioxide ($CO_2$) and other greenhouse gases in the atmosphere. Development and use of capture and storage technology in the underground formations contribute to the reduction of $CO_2$ emissions to the atmosphere.

The objective of this thesis is to analyse technology for capture and storage of carbon dioxide used in Norway.

The second objective is to make an application analysis of the technology of capture and storage of carbon dioxide on Russian shelf.

Risk analysis connected with carbon dioxide storage is the third objective of the paper.

The thesis supports the idea of climate change stabilisation about the global reduction of $CO_2$ emission. The method under research is the technology of capture and storage of $CO_2$. This method has been already adopted/tested in such countries as Norway and Australia. The research is based on technology adopted in the Sleipner gas field in Norway. This development was the world's first demonstration of CCS technology for a deep saline reservoir.

Removing carbon dioxide mechanism represents a conventional amine based process. Trapping mechanism of $CO_2$ is performed by creating a concentrated stream of $CO_2$ by applying high pressure. This makes it easy to transport $CO_2$ through the pipeline to storage. From an economic point of view, pipelines are a preferred method for long distance transportation of considerable amounts of $CO_2$. Depleted oil and gas fields are regarded as safe reservoirs for storage of $CO_2$ due to the historical trapping of oil, gas and quite often carbon dioxide as a natural gas mixture in millions of years.

From an economic point of view, the benefits may not outweigh the extra costs of $CO_2$ capture, but at the same time, there are known cases in which when injection of $CO_2$ into declining oil fields increased oil recovery.

## Acknowledgements

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I would also like to acknowledge my supervisor from Russia professor Kaplan S. Basniev of the Faculty of Reservoir Engineering at Gubkin Russian State University of Oil and Gas. His expertise, understanding, generous guidance and support made it possible for me to work on a topic that was of great interest to me. It was a pleasure working with him.

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I would like to thank my old friends from Russia and to my new friends from Norway, Mexico, Eritrea, Ecuador, Azerbaijan, India, and other countries from around the world. This journey would not be so extremely good and unforgettable without you.

## List of abbreviations

ALARP – As Low As Reasonably Possible

APEC – Asia-Pacific Economic Cooperation

API – American Petroleum Institute

BP – British Petroleum

BTOE – Billion Tonnes of Oil Equivalent

CCS – Carbon Capture and Storage

CO2CRC – The Cooperative Research Centre for Greenhouse Gas Technologies

ECBM – Enhanced Coal Bed Methane recovery

EIT – Economies In Transition

E&P – Exploration and Production

FL – Federal law

HF – Hydrate Formation

HXT – Horizontal X-mass tree

IEA – International Energy Agency

IGCC – Integrated Gasification Combined Cycle

IFPA – International Fuel & Power Association

IPCC – Intergovernmental Panel on Climate Change

L – Leakages

LPG – Liquefied Petroleum Gases

LTS – Low Temperature Separation

MDEA – Methyl diethanolamine

MEA – Monoethanolamine

MEG – Monoethylene Glycol

NGCC – Natural Gas Combined Cycle

OECD – Organization for Economic Cooperation and Development

OPF – Onshore Processing Facility

PC – Pulverised Coal

SB – System Breakdown

SOGM – Scandinavian Oil – Gas Magazine

SPS – Subsea Production System

SRC – State Committee for Mineral Reserves

TPES – Total Primary Energy Supply

TVD – Total Vertical Depth

UNO – United Nations Organization

XT – X-mas tree

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# Introduction

The concentration of greenhouse gases, such as $CO_2$, in the atmosphere, has gradually increased and reached a high level during the last years. Carbon dioxide emissions are mainly the result of fuel combustion. Different industrial processes lead to the $CO_2$ formation and therefore, to its emission.

The urgency of the research is determined by the problem of climate stabilisation. The main aim of modern science is to provide humanity with methodological, technical and technological real-world scenarios of the problem to solve.

The ways to reduce carbon dioxide emission and its concentration in the atmosphere are:

- Decreasing of energy demand with the help of enhancing effectiveness of energy transformation and/or equipment for its consumption;
- Energy carrier decarbonization;
- $CO_2$ absorption due to wider usage of absorbers with biological fixation;
- Reduction of volume of other greenhouse gases;
- Usage of the technology of capture and storage of carbon dioxide.

The topic of this thesis is a description of technology of capture and storage of carbon dioxide and application analysis of this technology on Russian shelf. Such technology is considered as one of the most effective variants for reducing carbon dioxide emissions to the atmosphere because of human activity.

The technology of capture and storage of carbon dioxide was investigated by a number of scientists and organisations and was firstly adopted in the Sleipner gas field in Norway. This was a good example of its worldwide implementation.

The technology of capture and storage of carbon dioxide first is associated with the capture and concentration of $CO_2$, its transportation, and storage. However, levels of technical excellence of individual components of the system are characterised differently. Some of them are widely used at a high level of the market, while others are still at the stage of developing and demonstrating.

Convection about global climate change was adopted in 1992. In this case, the technology of capture and storage of carbon dioxide is considered as a way for stabilisation of greenhouse gases concentrations in the atmosphere.

It is well known, that consumption of fossil fuels is increasing nowadays. Therefore, $CO_2$ emissions are increasing as well. Reduction scales depend on both levels of future releases and on the concentration of carbon dioxide in the air: the less the level of stabilisation and bigger initial emission, the bigger the necessity of an emission reduction of $CO_2$. In this context, the existence of technology of capture and storage of carbon dioxide can promote the emission reduction of greenhouse gases and contribute to approaching stabilisation.

The use of technology for capture and storage of carbon dioxide can essentially reduce the cost of stabilising. The interest in this is explained by the existing dependency on fossil fuel in the whole world (80% of all energy consumption), the high potential of emissions reduction of $CO_2$, and compatibility of technology with current energy infrastructures.

Russian Federation is one of the richest countries with hydrocarbons in the world. That determines the high level of $CO_2$ emissions within the country. In this case, the implementation of the technology of capture and storage of carbon dioxide seems to be helpful from the contribution of the Russian Federation to the climate stabilisation point of view.

The full technology adoption was not conducted in Russia until today. This fact justifies the scientific novelty of the thesis.

# Chapter 1. Carbon dioxide sources

This part of the thesis is devoted to carbon dioxide sources, their specifications and their dispersion around the world. Special attention is paid to key trends in $CO_2$ emissions from fuel combustion.

The earth's atmosphere is the layer of gases that surrounds the planet. The atmosphere is commonly known as air. The composition of the atmosphere is more or less stable. Generally, it consists of nitrogen, oxygen, argon, carbon dioxide and small amounts of other gases. A more detailed composite of the atmosphere is presented in Figure 1.1 below. [1]

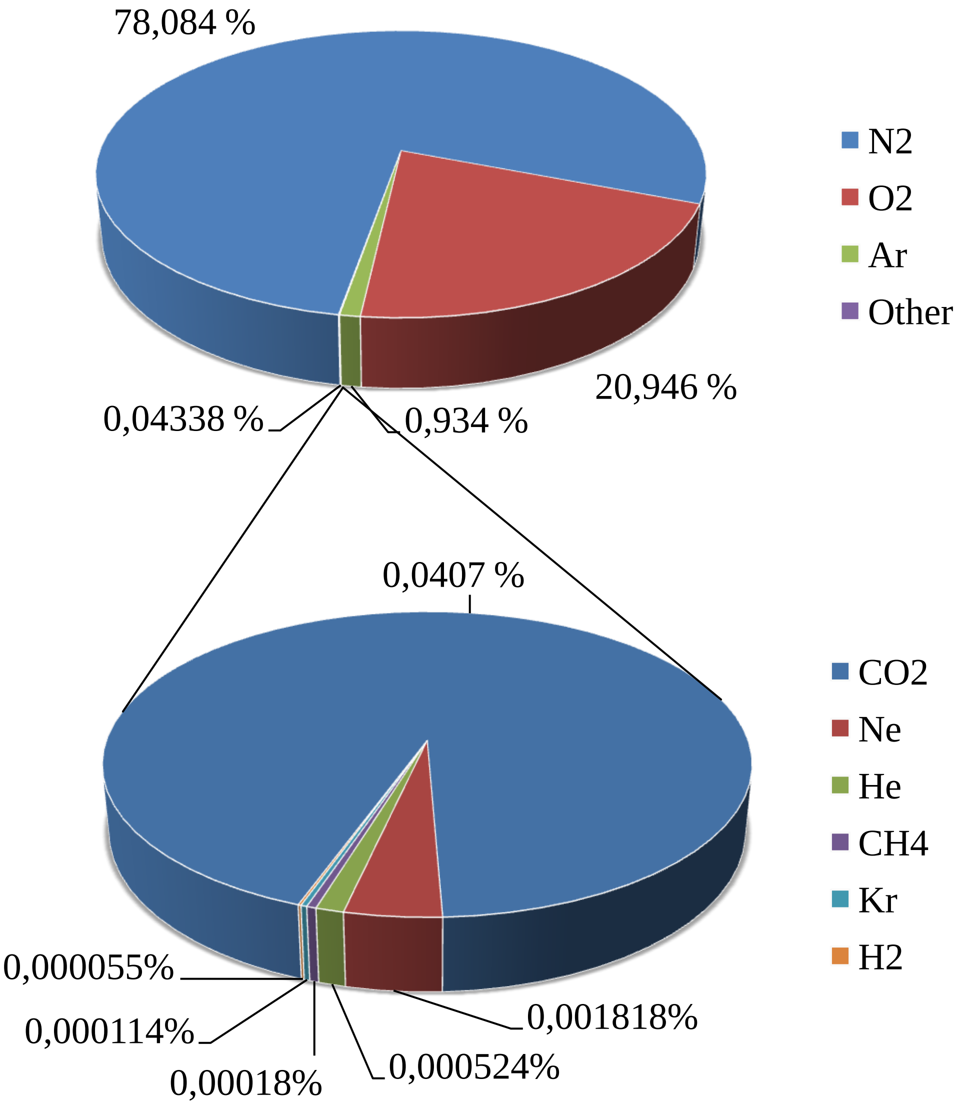

Fig.1.1. Composite of the Earth's atmosphere by volume [1]

In spite of its relatively small concentration, $CO_2$ poses as one of the most important components of the atmosphere. It is connected to both: contributing to the greenhouse effect and regulating Earth's surface temperature.

The concentration of carbon dioxide in the atmosphere has been increasing significantly over the past century. The average concentration of $CO_2$ in January 2017 of about 406.42 parts per million compared to preindustrial era level (280 ppm) was about 45% higher. [2]

There are two main sources of carbon dioxide – natural and human sources. Natural sources include ocean-atmosphere exchange, plant and animal respiration, soil respiration and decomposition, and volcanic eruption. The percentage distribution of listed sources is presented in Figure 1.2. [3]

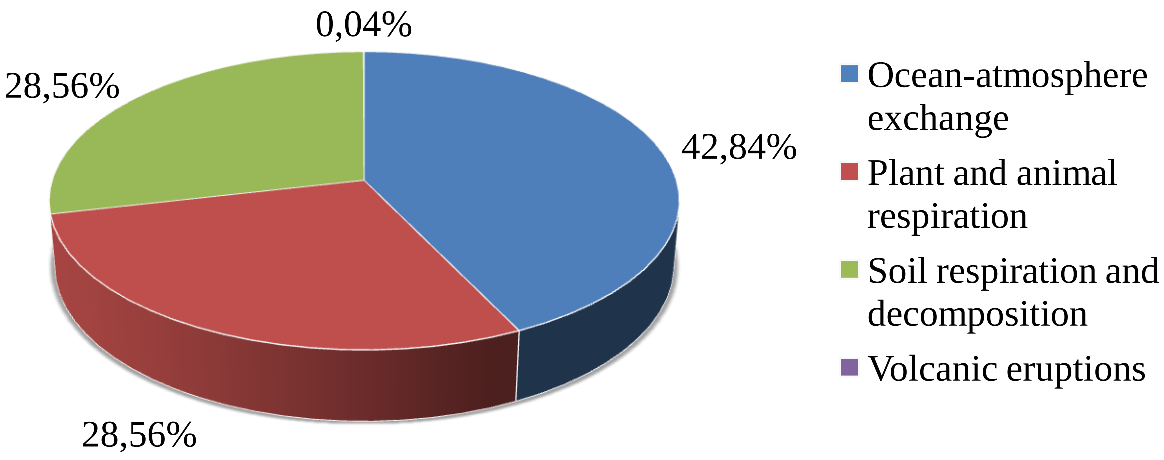

Fig. 1.2. Natural sources of carbon dioxide [3]

Man-made sources (anthropogenic sources) of $CO_2$ emissions are from burning fossil fuels, deforestation, industrial processes and other sources. The percentage distribution of listed sources is presented in Figure 1.3. [4]

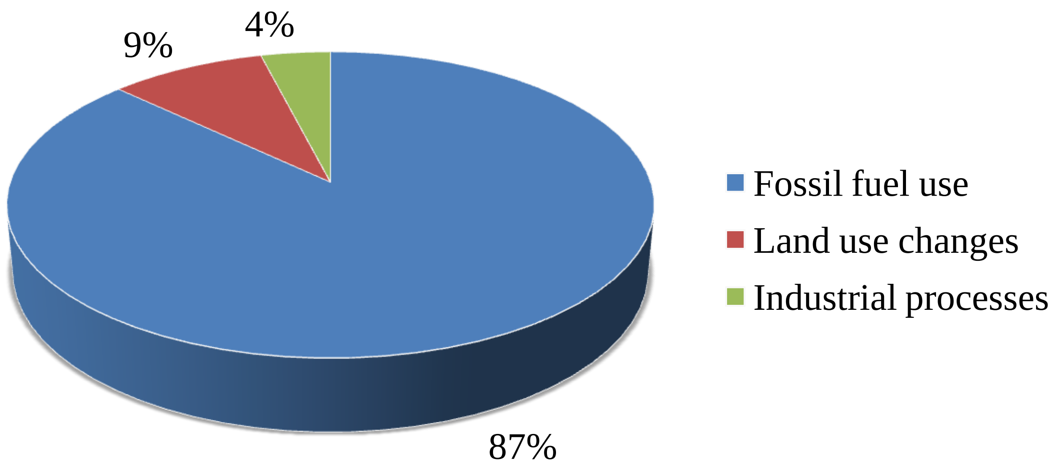

Fig. 1.3. Anthropogenic sources of carbon dioxide [4]

Anthropogenic sources produce less $CO_2$ than natural sources. For example, plant and animal respiration, as well as soil respiration and decomposition, produce 439 gigatons of carbon dioxide and absorb 450 gigatons of carbon dioxide. While fossil fuel use and land use changes just produce 29 GT of carbon dioxide. Detailed information is presented in Table 1.1. [5]

Table 1.1. Input and output volumes of carbon dioxide

| Source | Input volume, GT | Output volume, GT |
|---|---|---|
| Fossil fuel burning + Land use | 0 | 29 |
| Vegetation and Land | 450 | 439 |
| Ocean | 338 | 332 |

It is obvious, that human sources of carbon dioxide represent a tiny percentage of natural sources. On the other hand, the natural cycle adds and removes $CO_2$ to keep a balance, while humans add an extra amount of carbon dioxide without removing any. Such facts cause one thinking: what should people do to keep the balance?

According to materials of the World meeting about sustainable growth (Johannesburg, 2002) the International Energy Agency has verified that energy crisis will not threaten for the planet in the near future. Nevertheless, the crisis has already come. However, there are differences between different groups of countries. It can be explained by the condition and dynamic of industries, demand, export and import of primary energy resources and carbon dioxide emissions. [6]

There is a necessity to solve the question of anthropogenic source emission of carbon dioxide. Such question shall be considered from three different points of view: $CO_2$ sources by sector, $CO_2$ sources by fuel and $CO_2$ sources by region. These points are closely linked together. It is obvious that different industrial sectors require fossil fuel for development, and countries rich with fossil fuels, are able to build up the industry. Therefore, the details of the $CO_2$ sources are analysed.

### 1.1. Carbon dioxide sources by industrial sector

As was mentioned, the largest human source of carbon dioxide emission is from the combustion of fossil fuels. It produces almost 87% of human carbon dioxide emissions. Burning these fuels releases energy that is later, most commonly turned into heat, electricity or power for transportation.

Demand for energy is increasing annually. Such tendency is associated with worldwide economic growth and development. Global total primary energy supply increased by almost 150% between 1971 and 2014. It relates mainly to the increase in fossil fuel consumption, represented in Figure 1.4. [7]

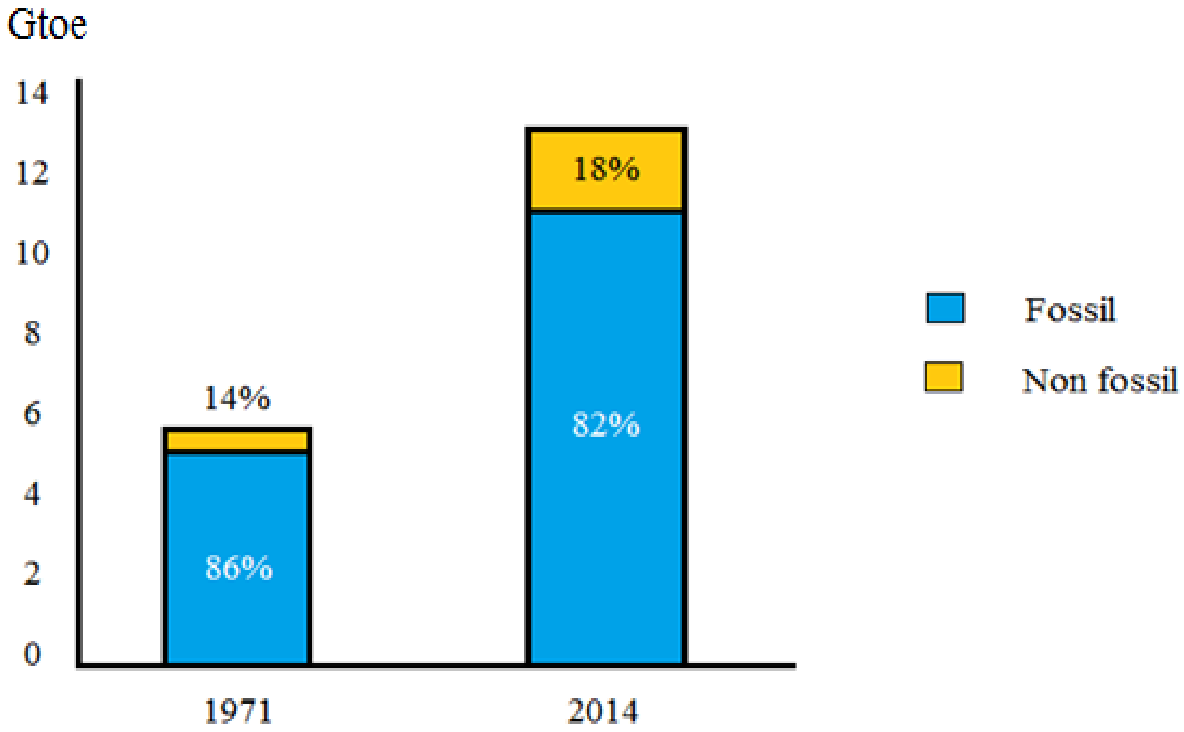

Fig. 1.4. The world primary energy supply [7]

Among the many human activities that produce greenhouse gases, the use of energy represents by far the largest source of emissions. It is well known, that the main source of energy was and still is a fossil fuel. That can be clearly understood from Figure 1.5 below. Fossil fuels are widely used for energy production, transportation, industrial processes and, of course, in everyday life. That, in its turn, entails carbon dioxide emissions. [8]

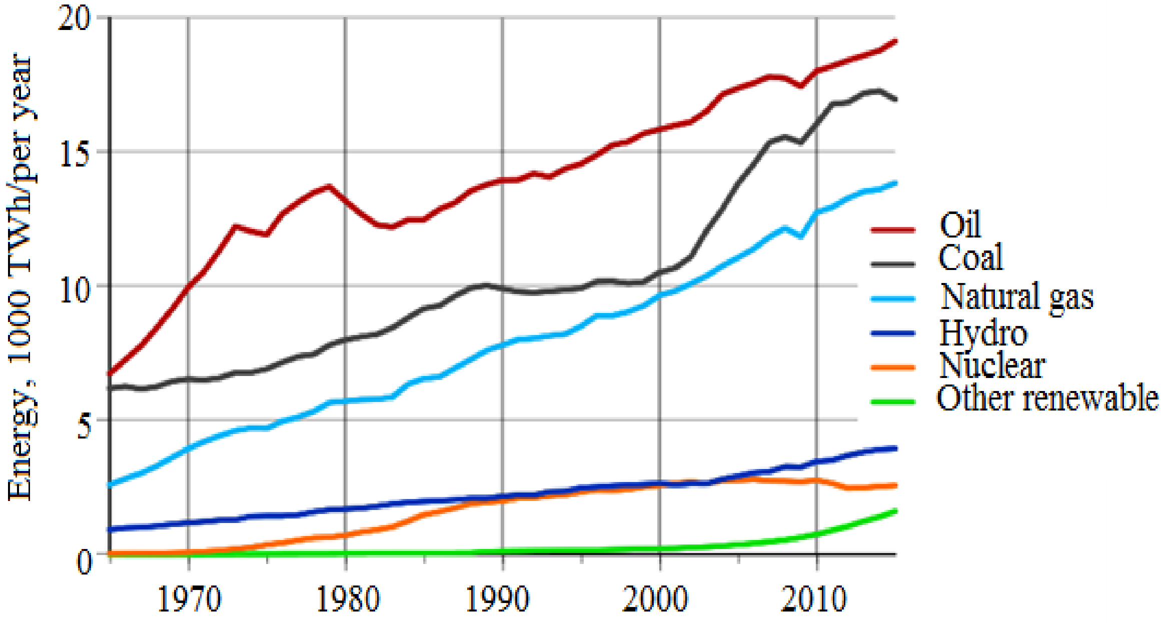

Fig. 1.5. The world increasing demand for energy [8]

The distribution of carbon dioxide emissions from fossil fuel combustion, which is used for different industrial sectors, is presented in Figure 1.6. Most fuels are used for electricity and heat generation. That, in its turn, gives a reason for the largest emissions of $CO_2$. The transportation sector and industrial sector use almost the same amount of fossil fuels and produce 22% and 20% of carbon dioxide emissions, respectively. [7]

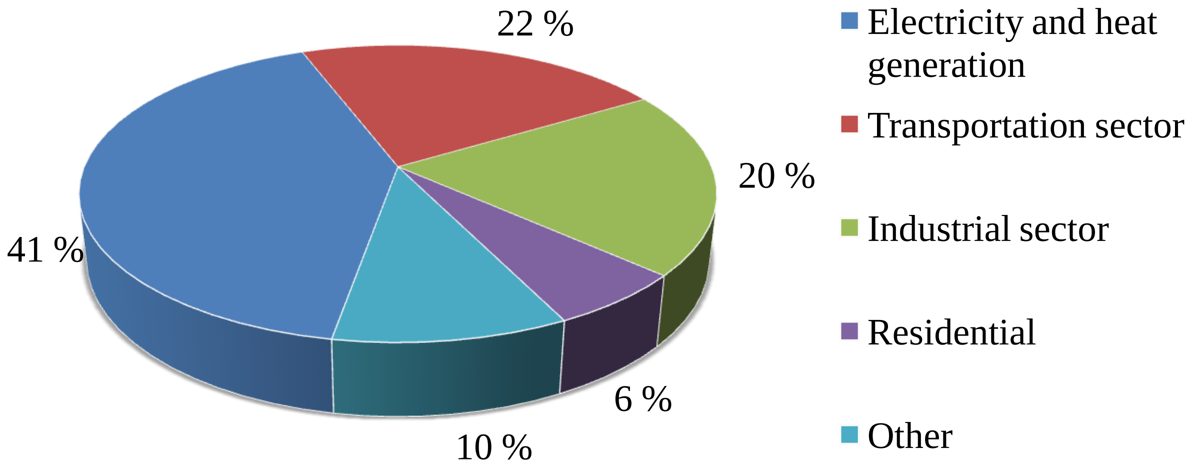

Fig. 1.6. Carbon dioxide emissions from fossil fuel combustion [7]

As it was mentioned before, the demand for energy is increasing annually. In a growing world demand for energy, fossil fuels play a key role in the upward trend in carbon dioxide emissions that is presented in Figure 1.7. [7]

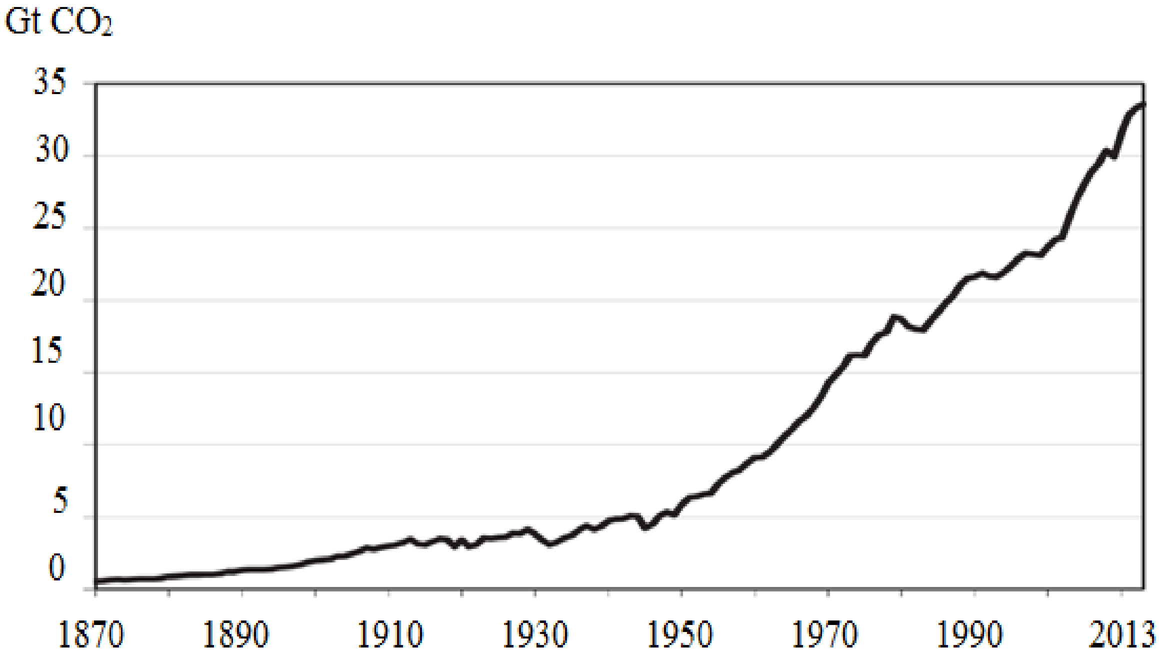

Fig. 1.7. Trend in $CO_2$ emissions from fossil fuel combustion [7]

According to the International Energy Agency's assessment, the world's energy consumption was more than 9.5 megatons of oil equivalent used for fuels in 2014. It resulted in global carbon dioxide emissions that reached about 32.4 $GtCO_2$. [9]

Humanity has increased its commitment to energy, mainly from fossil fuels. However, humankind does not pay attention to the consequences of the energy activity. Cumulative emission of carbon dioxide reaches more than 300 billion tonnes. This value according to the future industrial assessment could double during the next 30-40 years. Demand for fossil fuels does not allow stopping the growth of $CO_2$ emissions. The problems of climate stabilisation and maintaining the ecological balance on the Earth does not have a quick and easy solution. That results in a restriction of traditional energy sources development. [10]

## 1.2. Carbon dioxide sources by fossil fuel

Different fossil fuels produce miscellaneous amounts of carbon dioxide emissions due to varying carbon content per unit of energy released. For example, compared to natural gas, coal almost produces twice the emissions. Default carbon emission factors are:

- 15.3 tons of carbon emission per terajoule of energy for gas;
- 15.7-26.6 tC/TJ for oil (depends on the composition);
- 25.8-29.1 tC/TJ for coal.

More detailed data are presented in Table 1.2. [7]

Table 1.2. The world primary energy supply and $CO_2$ emissions: shares by fuel in 2014

| Energy source | Percent share | |
|---|---|---|
| | Total Primary Energy Supply (TPES) | $CO_2$ |
| Oil | 31% | 34% |
| Coal | 29% | 46% |
| Gas | 21% | 19% |
| Other | 19% | 1% |

In Table 1.2, “other”, includes nuclear, hydro, geothermal, solar, tide, wind, biofuels and waste.

In Figure 1.8, the percentage of carbon dioxide emissions from different types of fossil fuels are presented. [7]

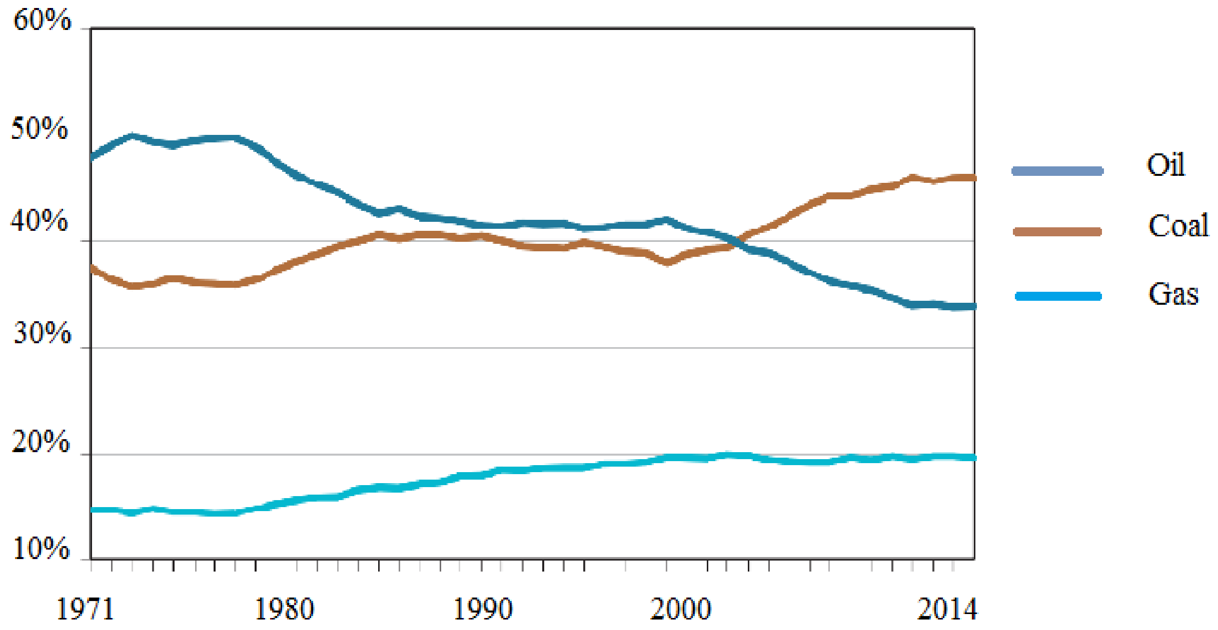

Fig. 1.8. Fuel shares in global $CO_2$ emissions

Carbon dioxide is widely held in nature and atmosphere and in natural gases and oil as well. The concentration of $CO_2$ is in the range of 10-15% of gas, gas condensate and gas oil fields. This value reaches 90-98% sometimes. For example, on the Michaii field (Hungary) the gas consists of 95% of $CO_2$ and 4.5% of $CH_4$. On the Veselovsky and Mejovskoye fields (Western Siberia), the concentration of carbon dioxide reaches 85 and 97% respectively.

The variety of $CO_2$ sources results in their wide distribution. The origination of carbon dioxide connects with the following processes: katagenesis and diagenesis of an organic substance, post-volcanic processes, thermo-catalytic transformation and hydrolysis of an organic substance, and others. [11]

## 1.3. Carbon dioxide sources by region

As different regions and countries have contrasting economic and industrial development, pictures change rapidly. However, there are four specific regions of emission concentration: North America, Europe, East Asia and South Asia. That can be explained because of the super activity of oil and gas consumption. Total energy consumption in all over the world and in these regions particularly is presented in Table 1.3. [7]

Table 1.3. The world primary energy consumption

| Country | Energy consumption |
|---|---|
| Asia (including China) | 40% |
| North America | 18% |
| Europe | 8% |
| Economies in transition countries (EIT) | 7% |
| Middle East | 5% |
| Latin America | 4% |
| Africa | 3% |
| Bunkers | 4% |
| Other | 11% |

The global geographical distribution of the biggest stationary sources and their closeness to potential storage places are the most important aspects that have to be considered to estimate the potential of the technology of capture and storage of carbon dioxide. Emissions of $CO_2$ from residential, commercial and transport sectors are not analysed in this thesis, whereas they can be considered as an individual, insignificant, and often the mobile source. Therefore, such sources are not available for the technology of capture and storage.

As was mentioned, fossil fuel consumption is the biggest source of global carbon dioxide emissions. The largest stationary sources represent more than 60% of total releases. However, not all of these sources are suitable for capturing.

The majority of the largest sources of carbon dioxide emissions is characterised by $CO_2$ concentration that is less than 15% nowadays. A small proportion (less than 2%) of industrial sources that use fossil fuels has a concentration of carbon dioxide more than 95%. Analyses of these sources show that $CO_2$ emissions are larger than 360 megatons per year. Therefore, such sources are potential candidates for implementing the technology of capture and storage of carbon dioxide.

The most important issue in the realisation of carbon dioxide capture and storage (CCS) technology, is the distance between the emission sources and the locations for storage. This question plays a considerable role in emission reduction. In Figures 1.9 and 1.10 below, the largest stationary sources of carbon dioxide emissions and potential places for storage are presented. [12]

Fig. 1.9. The global distribution of the biggest sources of carbon dioxide [12]

These figures show that there exists the potential for correlating between sources and prospecting sedimentary basins. Nevertheless, it is important to take into consideration that not all the possible storage locations were identified as suitable reservoirs for storage. More accurate and detailed surveys are required to estimate their suitability.

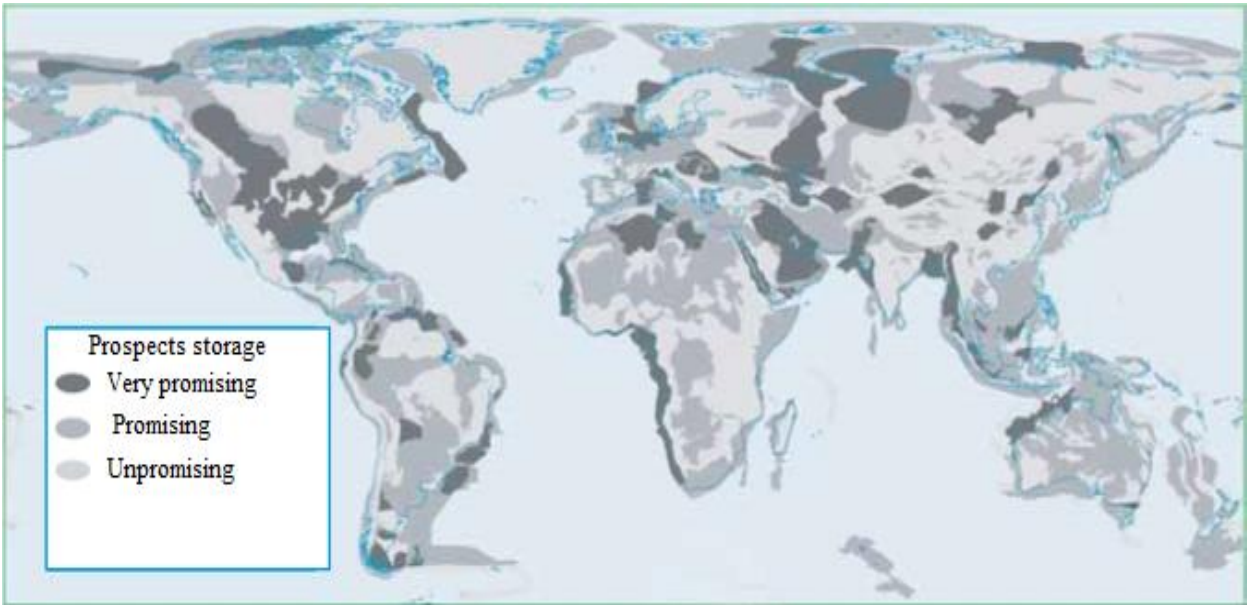

Fig. 1.10. Prospecting sedimentary basins for storage of carbon dioxide [12]

Countries with high emission rates should consider the possibility of implementing the technology of capture and storage of carbon dioxide. Top ten emitting countries and their emission rates are presented in Figure 1.11. The tendency of emissions growing takes place. The trend of increasing releases is presented in Figure 1.12. [13]

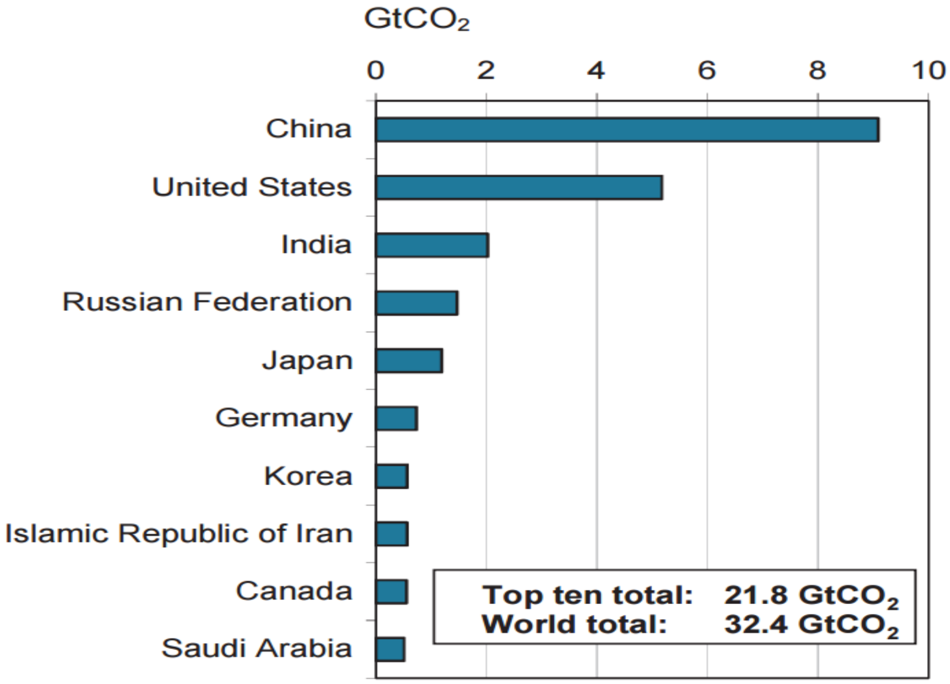

Fig. 1.11. Top ten emitting countries in 2014 [13]

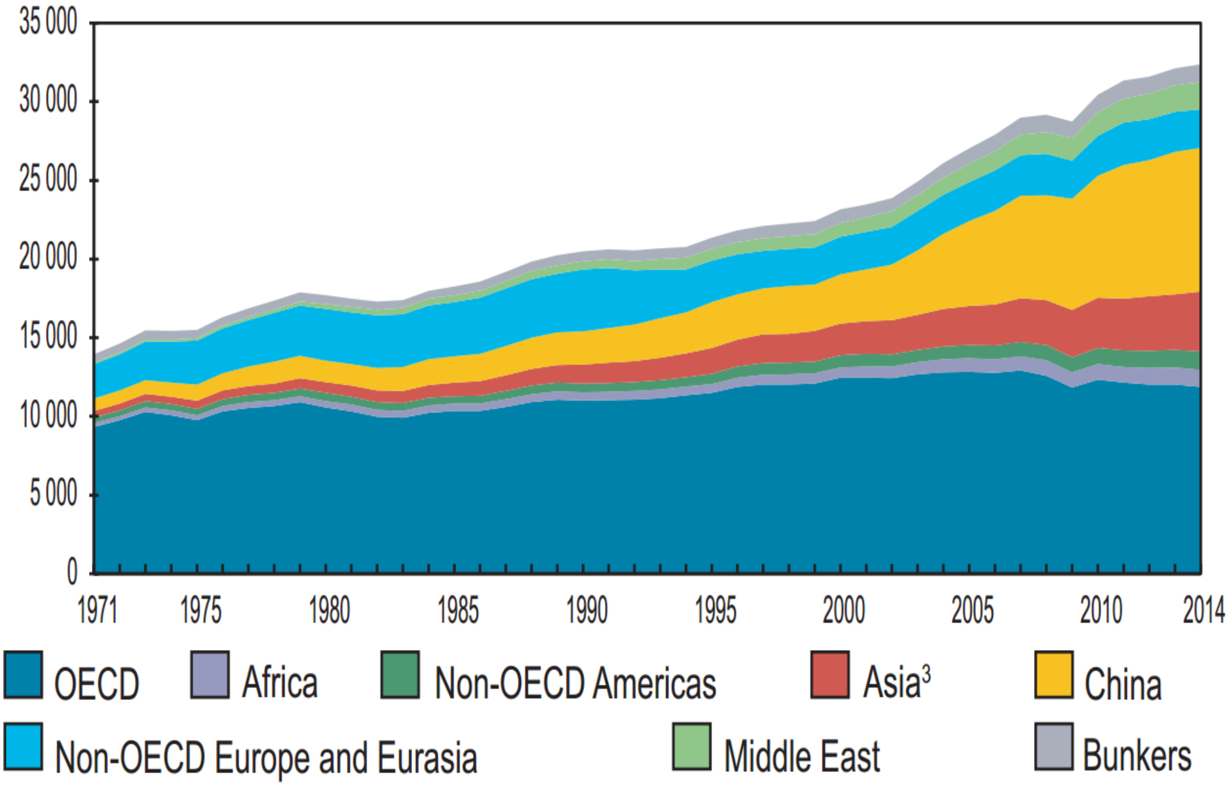

Fig. 1.12. World $CO_2$ emissions from fuel combustion from 1971 to 2014 by region (Mt of $CO_2$) [13]

Such tendency should not be ignored. Dependency on fossil fuels exists. Therefore, the demand for oil and gas is still increasing. This, in its turn, results in carbon dioxide emissions growth. This sequence explains the necessity of implementing the technology of capture and storage of $CO_2$.

As a conclusion to this part of the thesis, the following sequence has been identified: industrialised countries use fossil fuels as a primary source of energy. From this statement, all sources of carbon dioxide emissions are obvious: industry (sector), fossil fuels and regions (countries). All considered points are connected and represent the integrated chain of the climate stabilisation problem.

Russia is an industrialised country that has huge reserves and resources of hydrocarbons. That explains large-tonnage emissions of $CO_2$ to the atmosphere and the necessity for the technology of capture and storage of carbon dioxide. Probably, the best example of a country that uses this technology is its originator – Norway.

# Chapter 2. Consequences of carbon dioxide emissions

The consequences of carbon dioxide emissions are the main topic in this part of the master's thesis. Strategies to reduce emissions are also described.

An environmental benefit analysis shows that there are quite a lot of consequences of carbon dioxide emissions, as well as many causes. The concentration of carbon dioxide in the atmosphere increases from year to year.

As it was already said, fossil fuel burning and land use produce about 29 GT of carbon dioxide per year. While the adsorbed amount is equal to zero GT.

Emissions of $CO_2$ mainly lead to global climate change. This affects the rising of sea level as a result from icebergs melting, increasing the acidity of water, permafrost dissolution, etc. Climate stabilisation requires a reduction of the global carbon dioxide emissions to 50 – 85% by 2050. [14]

The first and most important consequence of carbon dioxide emissions is the average global temperature change. The Earth transforms the energy from the sun to infrared waves that travel from our planet in space. Greenhouse gases, like carbon dioxide, preclude this transferring, by partly absorbing infrared radiation and holding the energy in the atmosphere. Emissions of $CO_2$ lead to an increase of the trapped energy in the atmosphere, resulting in a temperature rise.

The global temperature rise causes many changes, such as sea-level rise, the amount and distribution of atmospheric fallouts. As a result, natural disasters, like overflowing, droughts, hurricanes, and others, may become more frequent. Global warming might cause some the consequences listed before, due to the increase of the energy on Earth that invites the atmosphere to be more aggressive.

## 2.1. Global consequences of carbon dioxide emissions

On Figure 2.1 below, we can appreciate the difference in global temperature change between two scenarios: reality – natural and human factors and modelling – natural factors only. [14]

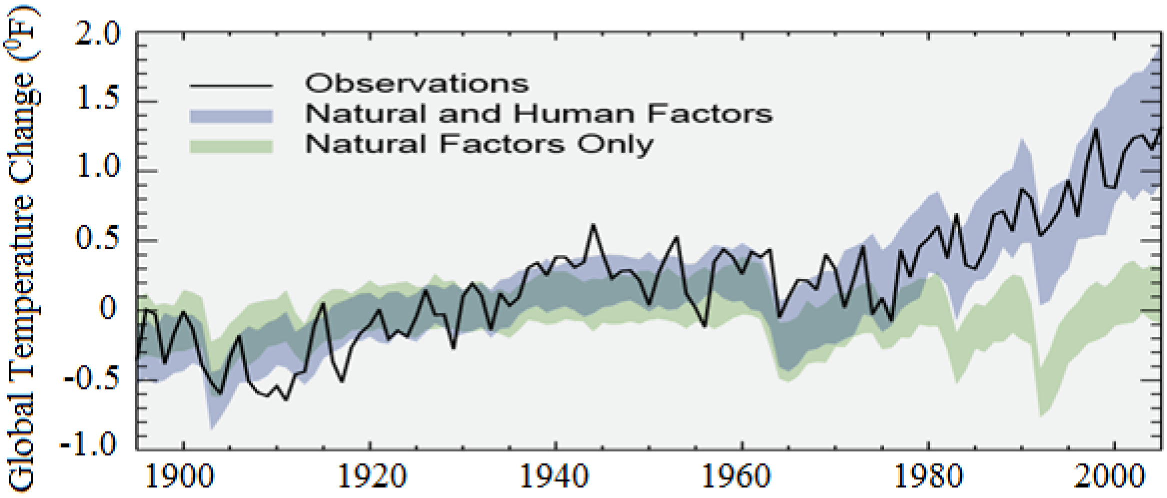

Fig. 2.1. Separating human and natural influences on climate [14]

It is obvious that humanity influences the temperature on Earth. People interact with the planet forgetting that it is a very fragile system, which we should keep in balance. According to the Figure 2.1 above, temperature changes due to human activity are about 1 $^0$F or more than 0.6 $^0$C. Such fluctuation leads to unpredicted consequences surely.

Global temperature changing involves not only warming. The salinity of the World Ocean, air humidity, rain precipitation behaviour, arctic ice melting, are changing as well.

As it was mentioned, the average concentration of carbon dioxide in the atmosphere is larger than 406.42 ppm nowadays. Once the peak is reached, it certainly will cause changes in the climate. First, it will affect precipitations. According to the proceedings of the National Academy of Sciences of the United States of America, changes will look like they are represented in Figure 2.2.

The quasi-equilibrium carbon dioxide concentrations that are represented correspond to 40% of the remaining in the long term as mentioned above. As we can see, changes in precipitations per degree are derived for each region and for four specific regions of $CO_2$ emission concentrations that were mentioned earlier particularly. Precipitation changes will touch typical major regional droughts as well. The yellow box indicates these changes. [15]

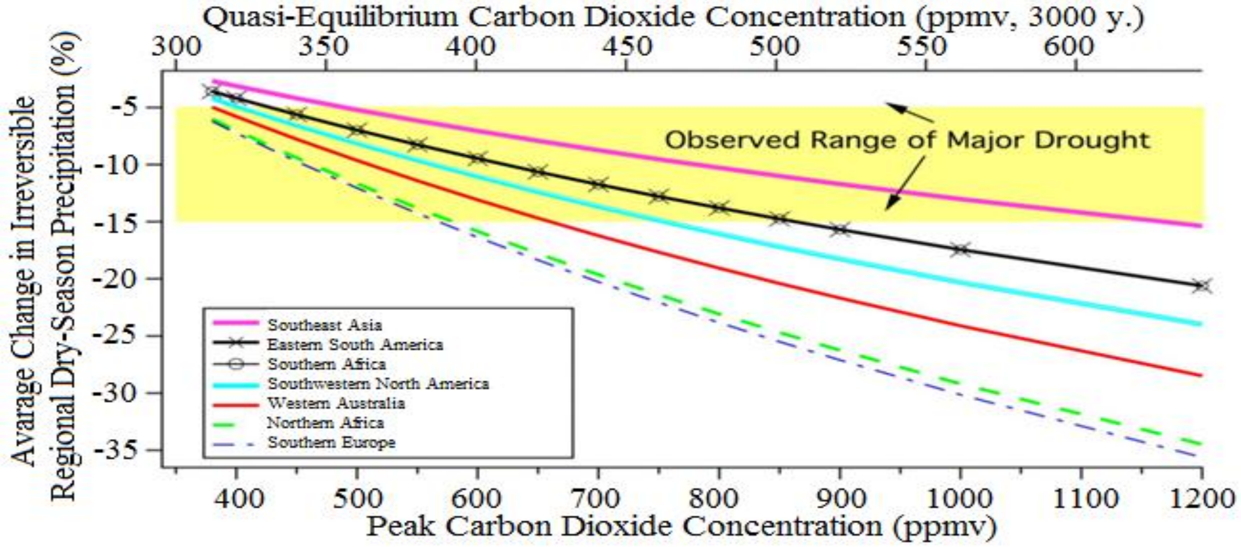

Fig. 2.2. Estimate of expected irreversible dry – season precipitation changes for the regions [15]

Secondly, irreversible increase in the average global warming can occur and it will result in an irreversible sea-level rise due to icebergs melting. The tendency of temperature and sea level changing is shown in Figure 2.3. [15]

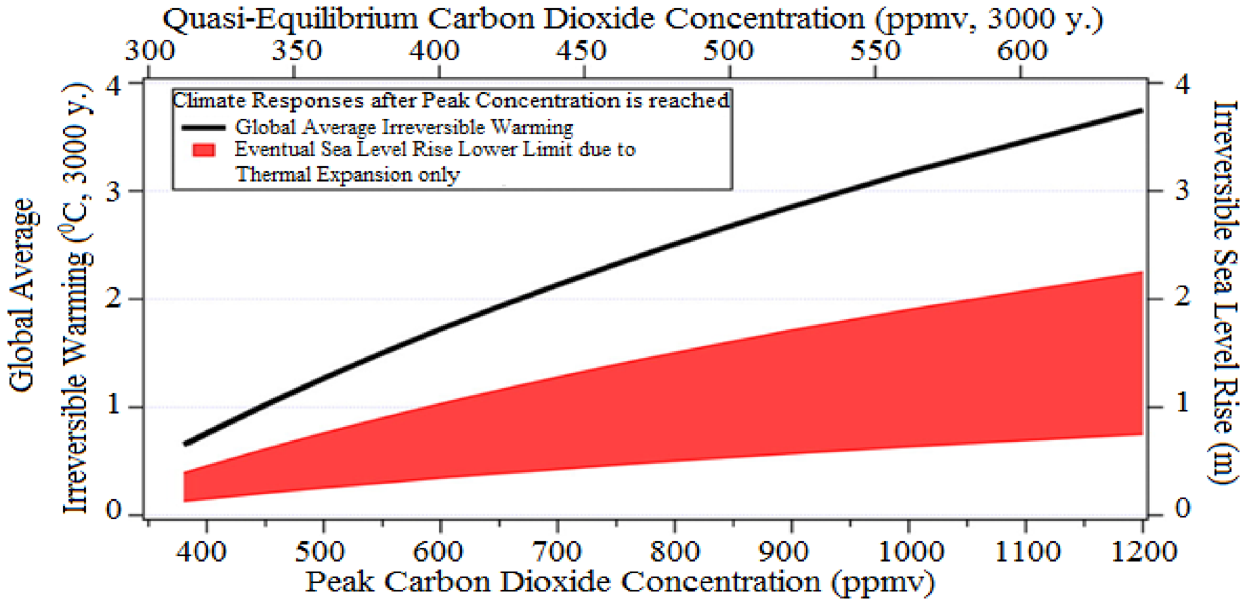

Fig. 2.3. Average temperature and sea level changing [15]

Apart from global temperature change and ensuing consequences, water migrates with the flux of carbon dioxide emissions simultaneously. $CO_2$ releasing by convection has quantified water-holding capacity. Meaning that the emissions are travelling in the form of a gas-vapor mixture.

According to V.I. Petrenko and contributors, $93*10^{12}$ $m^3$ of carbon dioxide are emitted to the atmosphere annually. Water-holding capacity of $CO_2$ is about 0.66 $g/m^3$ at the average temperature of the Earth 13 $^0C$ and atmospheric pressure 101.3 kPa. Such conditions contribute to $76*10^{12}$ $m^3$ of aqueous vapour and $61*10^9$ kg of water emission. Compare to other gases released into the atmosphere, carbon dioxide takes a major part of the water transporting gases – 90.4%.

Such transportation of water through the gases to the atmosphere is additional for direct surface, seas and ocean evaporation. This process of constrained evaporation is called air evaporation.

The described process influences on the different natural phenomenon. For example, it can aggravate the steam condensation. [16]

## 2.2. Consequences of industrial carbon dioxide emissions

As it was mentioned, the biggest source of anthropogenic carbon dioxide emissions is fossil fuel combustion. Environmental hazards are classified as biological, mechanical, chemical, and physical. They have different forms of impact on the surroundings and consequences.

Carbon dioxide or $CO_2$ – colourless, heavy, poor reactive gas. It has slightly acid odour and flavour at a low temperature. Properties of carbon dioxide are presented in Table 2.1. Carbon dioxide does not have toxic effects if its concentration is less than 1% in the air. If its concentration is more than 4-5% $CO_2$ influence on respiratory organs increasing breathing rhythm. Strong intoxication is possible if the concentration of gas is larger than 10%. [11]

Carbon dioxide has a drug action on people. It can change men’s behaviour (gait, papillary reaction, etc.) and innervate mucous membrane. The normal concentration of $CO_2$ in the air for people is about 0.04%. [17]

Table 2.1. Properties of $CO_2$

| Properties | | Values |
|---|---|---|
| Chemical formula | | $CO_2$ |
| Molecular mass Mr | | 44.011 |
| Individual gas constant, J/(kg*K) | | 188.907 |
| Boiling point under pressure 0.101 MPa, K | | 467.82 |
| Bottlenecks (critical parameters) | Temperature, K | 304.20 |
| | Pressure, MPa | 7.381 |
| | Density, kg/m$^3$ | 468 |
| Density under pressure 0.101 MPa and temperature 273.15 K | | 1.9767 |
| Specific gravity of gas | | 1.5288 |
| Density under pressure 0.101 MPa and temperature 293.15 K | | 1.8307 |
| Specific heat capacity, kJ/(kg*K) | Under constant pressure | 0.8148 |
| | Under constant volume | 0.6263 |
| Dynamic viscosity, MPa*sec | | 139 |
| Critical compression coefficient | | 0.274 |
| Critical molar volume, m$^3$/mol | | 94 |
| Acentricity factor | | 0.231 |

### 2.3. Global and industrial strategies for carbon dioxide emissions preventing

The obviation of carbon dioxide emissions could be considered from the local and global point of view. At the same time, we should remember that the local reduction of releases would favourably affect a global reduction.

From a local point of view, there are several types of reduction of carbon dioxide emissions in the places of oil and gas production. They are planning, technological and special.

Planning measures include actions such as a sanitary protection zone organisation, centralization of technological communications, emissions centralizations, vent intake, administrative and production zone organisation, etc.

Technological measures could be improving the technological scheme, removal of repugnant substances, reorientation of the industry or its decommissioning, replace of periodic processes by continuous operations, etc.

The special measure is about changing of geometrical adjectives of carbon dioxide sources. [17]

As it was mentioned, reduction of carbon dioxide emissions is required for climate stabilisation that can be achieved by different strategies. [14]

The first strategy for emission reduction is improving the efficiency of the energy. This can be achieved by improving the insulation of buildings, driving more fuel-efficient vehicles, using more efficient electrical appliances. These are ways to reduce energy consumption and, therefore, emissions of carbon dioxide as well.

The second one is the strategy of energy conservation. Reducing energy demand can be obtained by reducing personal energy use. It can be done by turning the lights and electronics off, for example, when not in use. Reducing distances travelled in vehicles is another way to reduce fuel consumption. These are ways to reduce carbon dioxide emissions through energy conservation.

The third strategy is fuel switching. There are many different renewable resources. However, people still use fossil fuel mainly. Producing more energy from renewable resources and using fuels with lower carbon contents, are also ways to reduce $CO_2$ emissions.

The next one and the most interesting for oil and gas industry is the strategy of carbon capture and storage. This method allows reducing carbon dioxide emissions greatly. This thesis is devoted exactly to this technology.

The described consequences of $CO_2$ emissions are only a few among much more. It is important to take into account that the behaviour of the weather is unpredictable. Therefore, the effects of climate change, because of carbon dioxide emissions and other greenhouse gases releases could be more severe. On the other hand, the planet is going through its own cycles, such as the ice era. However, it does not mean that humanity should use natural resources and disregard the results of its activity. Anyway, it is vital to stabilise climate change by reducing the concentration of greenhouse gases in the atmosphere. This indicates that the necessity of CCS technology actually takes place.

An experience of realisation and usage of this kind of technology exists. This technology has been already adopted/tested in countries like Norway and Australia. The first demonstration of CCS technology for a deep saline reservoir has been taken on the Sleipner gas field in Norway. The next section of the paper is devoted to a description of Sleipner gas field parameters, conditions and explanations on why this technology was needed.

# Chapter 3. Analysis of the technology of capture and storage of carbon dioxide

This part of the thesis is devoted to the description of the technology of capture and storage of carbon dioxide used in the Sleipner gas field in Norway. It also covers different aspects of technological accomplishments and possible improvements of different components of the technology.

As shown previously, fossil fuels are the main source of carbon dioxide emissions. This is explained by its wide usage for different industrial processes, such as the energy industry. In this case, power plants and large-scale industrial processes are primary candidates for capture and storage of $CO_2$. Analysis of the global distribution of sources and prospecting sedimentary basins for storage shows that the possibility of applying this technology is quite high.

However, this question should be considered not only from the geological and location point of view. First, the possibility of implementation of the technology of capture and storage of carbon dioxide is associated with the technological and technical side of the question. To understand the availability of the plant or other industrial processes to capture and prospecting sedimentary basins for storage of $CO_{2,}$ it is necessary to nipple down all components of the system and its operation concepts.

The technology of capture and storage of carbon dioxide, first of all, is associated with the capture and concentration of $CO_2$, its transportation, and storage. It should be noted that all of these components have a different level of technological accomplishments. Specifications and development levels of each of the stages are presented in Table 3.1. [12]

According to this data, the technology of capture and storage has not reached a high level of accomplishments. Therefore, further development and investigations are necessary, especially to its main components – capture and storage. It means that the researched topic of this project is of current interest. For future development of the technology, the accumulated experience of realisation can be used.

Table 3.1. Level of accomplishments of components

| Component | Technology | Level of development |
|---|---|---|
| Capture | After combustion | Economic feasibility |
| | Before combustion | Economic feasibility |
| Transportation | Pipeline | High development |
| | Tankers, ships | Economic feasibility |
| Geological storage | Increase oil recovery | High development |
| | Gas or oil fields | Economic feasibility |
| | Saline formations | Economic feasibility |
| | Enhanced coal bed methane recovery | Demonstration phase |
| Ocean storage | Direct injection (dissolution) | Research stage |
| | Direct injection (lake – type) | Research stage |
| Industrial usage of $CO_2$ | - | High development |

### 3.1. Carbon dioxide capture processes

The main objective of this step is to produce a nearly pure concentrated stream of carbon dioxide. It requires high pressure and commitment for further transportation to a storage site.

Capture of carbon dioxide begins at the separation step. This process is well characterised. A wide variety of separation is known and used nowadays. Applications separating $CO_2$ in large industrial plants, including natural gas treatment plants and ammonia production facilities, are already in operation today.

There are three main approaches to capturing the carbon dioxide generated from a primary fossil fuel (coal, natural gas or oil), biomass, or a mixture of these fuels: post-combustion systems, pre-combustions systems, and oxyfuel combustion systems. The application of one kind or another depends on the process or power plant. [12]

The concept of the post-combustion system is based on $CO_2$ separation after combustion of the primary fuel in the air. This system normally uses a liquid solvent. It equates to capture the small fraction of carbon dioxide that is presented in a flue gas stream. An organic solvent such as monoethanolamine (MEA) is used for current post-combustion capture systems for a modern pulverised coal (PC) power plant or natural gas combined cycle (NGCC) power plant.

The pre-combustion system produces a mixture that consists mainly of carbon monoxide and hydrogen by processing the primary fuel in a reactor with steam and air or oxygen. Then, the CO reacts with the steam in a second reactor and as a result, additional hydrogen, together with carbon dioxide, is produced. The resulting mixture of hydrogen and $CO_2$ can then be separated into the $CO_2$ gas stream and a stream of hydrogen. The pre-combustion system is more favourable for carbon dioxide separation compared to post-combustion and is used at power plants that implement an integrated gasification combined cycle (IGCC) technology.

Oxyfuel combustion system mainly produces water vapour flue gas with a high concentration greater than 80% by volume of carbon dioxide. This system uses oxygen instead of air for combustion of the primary fuel. Despite high technological results of the system, oxyfuel combustion is in the demonstration phase.

Figure 3.1 shows a schematic diagram of the systems described. As it was noted, all systems involve the separation of carbon dioxide. This step can be accomplished by means of physical or chemical solvents, membranes, solid sorbents, or by cryogenic separation. [18]

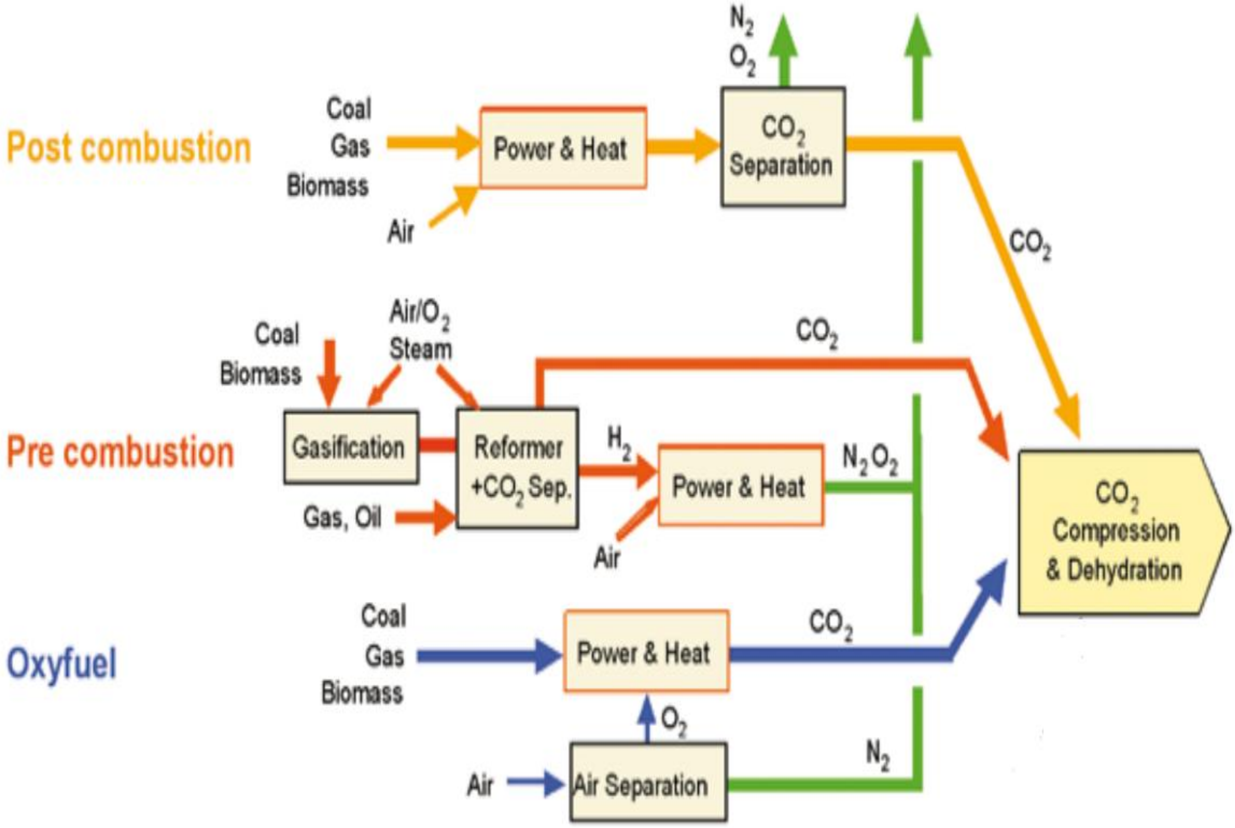

Fig. 3.1. Overview of $CO_2$ capture processes and systems [18]

## 3.2. Carbon dioxide transportation methods

The next step of the technology of capture and storage of carbon dioxide is the transportation of the concentrated $CO_2$ stream and utilisation of by-products. The transportation methods depend on the location of the storage site. In some cases, plants are located directly above prospecting sedimentary basins for storage. However, such opportunity and simplification are not always available.

The most common method for transporting carbon dioxide is a pipeline. This type of transportation operates as a mature market technology nowadays. In addition, $CO_2$ can be transported as a liquid in ships, road or rail tankers. All the listed kinds of $CO_2$ require special conditions.

Transportation of carbon dioxide by pipelines has taken its history since the 1970s. The first long-distance $CO_2$ pipeline was operating in the United States. It was used for the transportation of more than 40 $MtCO_2$ per annum over 2500 km of pipeline. This pipeline operates in the “dense phase” mode, and at ambient temperature and high pressure. One of the most important features of this type of transportation is the maintenance of high pressure above eight MPa, in order to avoid two-phase flow regimes and to increase the density of the carbon dioxide. This makes it easier and less costly to transport. That is why compressors at the upstream end and intermediate (booster) compressors were used to drive the flow.

However, transportation by pipelines is not always the cheapest way. If $CO_2$ must be moved over long distances or overseas, a more economically attractive way of transportation becomes transport of carbon dioxide by ship. This kind of transportation should carry $CO_2$ in insulated tanks at a temperature significantly below the surrounding, and at much lower pressure (typically at 0.7 MPa). Transportation of liquefied carbon dioxide technology is similar to liquefied petroleum gases (LPG) transportation. The difference is only a limited demand of $CO_2$.

Road and rail tankers are one of the possible ways of transportation. This type of transportation should provide almost the same conditions as the previous one. Typically, such systems transport carbon dioxide at a temperature of -20 $^0$C and at 2

MPa pressure. It seems to be the easiest way, but on the other hand, it is uneconomical, compared to pipelines and ships, and unlikely to be relevant to large-scale CCS. The free pass for this type of transportation is a very small scale.

A key aspect of the choice of the type of transportation is its cost. In Figure 3.2 below the cost of different types of transportation is presented. [18]

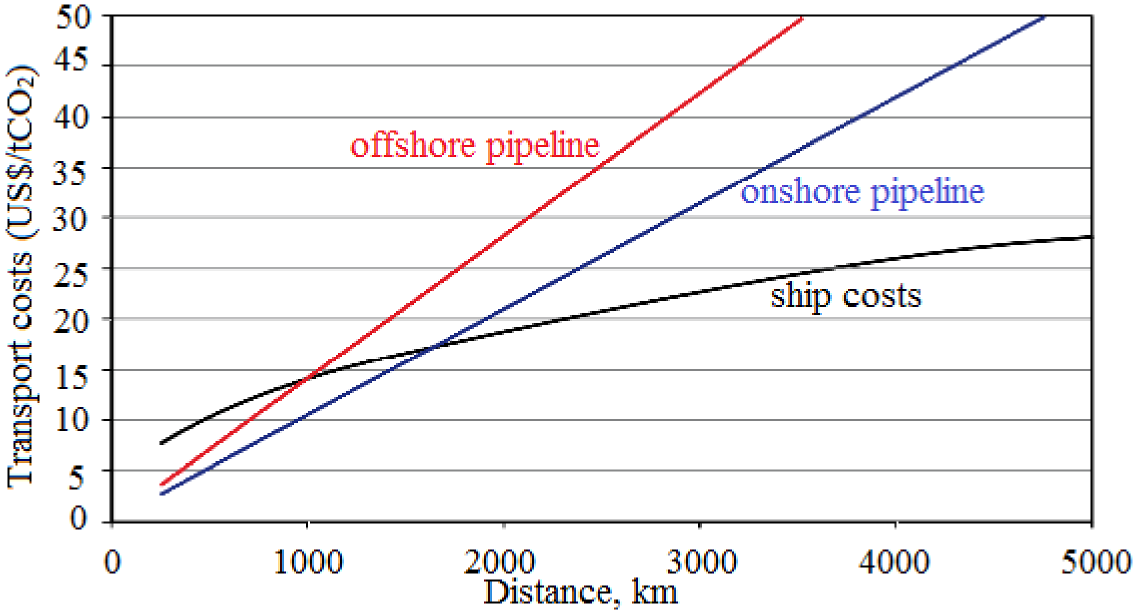

Fig. 3.2. Transport costs for offshore pipeline, onshore pipeline and ship transport [18]

In every case, the costs depend strongly on the distance and the quantity transported. In the case of pipelines, the pacing factor in the costs is the location of the pipeline. It is obvious that onshore pipelines are significantly cheaper than offshore. Figure 17 shows pipeline and marine transportation costs. Transportation by ship is cheaper for distances over 1500 km. However, on the other hand, the amount of transportable carbon dioxide is smaller than a few million tonnes per annum.

Besides costs, one of the most important parameters influencing the choice of the transportation system is the type of storage: geological or ocean. This thesis is devoted to geological storage. Nevertheless, it stands to mention that the most suitable transport system in ocean storage depends on the injection method: from a stationary floating vessel, a moving ship, or a pipeline from the shore.

### 3.3. Carbon dioxide geological storage

As it was mentioned, two different types of carbon dioxide storage exist. They are geological storage and ocean storage. This thesis includes the description and features of geological storage.

Geological storage of carbon dioxide represents an injection of the concentrated stream of $CO_2$ into a rock formation below the earth’s surface. In this case, three types of geological storage could be considered: oil and gas reservoirs, deep saline formations and unprofitable coal beds. It is obvious that the listed types have favourable properties to hold and keep carbon dioxide. Aside from this, suitable storage formation can occur in both onshore and offshore sedimentary basins. In Figure 3.3 below, an overview of geological storage options is presented. [18]

Besides the storing $CO_2$, geological storage can be used for enhancing oil and gas recovery as well as enhance coal bed methane recovery. However, the option of storing and ECBM recovery is still in the demonstration phase as it was shown in Table 3.1.

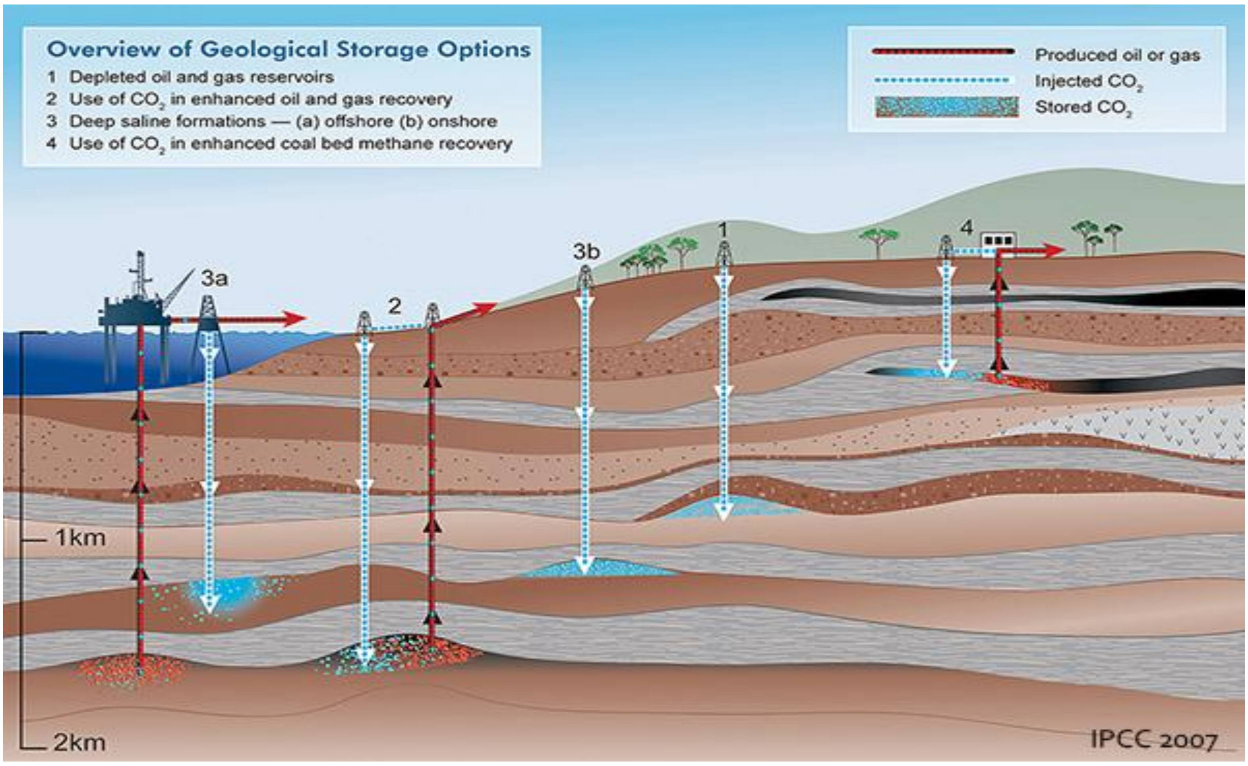

Fig. 3.3. Methods for storing carbon dioxide in deep underground geological formations [18]

Storage technology and mechanisms present almost the same technologies that are used in the oil and gas exploration and production industry. However, due to toxic and corrosion activity of the injected product, these technologies are being improved and developed further for the design and operation of geological storage.

The main issue of the storing technology is to provide the conditions under which injected carbon dioxide will be kept in the liquid or supercritical state. This explains that generally, $CO_2$ storage is kept at depths below 800 m. Required conditions contribute to the density of carbon dioxide by 50 to 80% of the density of water. Such density is close to the density of crude oil. That in its turn results in Archimedes force that tends to migrate $CO_2$ upwards. During the injection, $CO_2$ compresses and fills the pore volume. This provides displacing of the in-situ fluids. From the pore volume point of view, oil and gas reservoirs have advantages compared to the saline formations. The displacement of fluids can result in most of the pore place and, consequently, most of the volume that is available for $CO_2$ storage. Saline formations possess a lower volume about 30% of the total rock volume.

The primary objective of the storage is to trap carbon dioxide underground. Therefore, the most important component of this mechanism is well-sealed cap rock. This cap rock represents a physical trapping that blocks upward migration of the injected $CO_2$. An impermeable layer of shale and clay rock could be considered as cap rock. Apart from the cap rock, capillary forces could provide additional physical trapping that can hold the carbon dioxide in the pore volume of the formation. However, the described conditions do not always prevent the lateral migration of $CO_2$. In this case, additional mechanisms are required for the long-term entrapment.

Another type of trapping is the geochemical mechanism. It consists of a reaction between carbon dioxide, in-situ fluids and host formation. First, $CO_2$ is dissolved in the formation water that makes it heavier and therefore sinks down into the rock. After millions of years, the part of the injected fluid will be converted to solid carbonate minerals due to a chemical reaction between the dissolved carbon dioxide and rock minerals that form an ionic species.

Storing carbon dioxide in coal formations or organic-rich shales connects to another type of trapping. In these cases, $CO_2$ absorbs replacing gases. This kind of trapping usually takes place at shallow depths and is suitable for the pressure and temperature remain stable.

As it was mentioned, technologies and mechanisms used for geological storage of carbon dioxide are almost the same as the technologies applied in oil and gas industry. It means that the costs for this option are highly reliable in spite of lower the technical potential. On the other hand, due to the broad variability of factors influenced on the path of the technology realisation, costs are varied as well.

It is obvious that the costs for onshore, shallow, high permeability reservoirs will be lower. Storage sites where wells and infrastructure may be re-used have lower costs. For offshore, deep and so on reservoirs, the costs of the storage will be quite high. However, if storage technology is combined with the enhanced oil recovery, enhanced gas recovery or enhanced coal bed methane recovery, the total costs of implementation could be reduced. [18]

### 3.4. Sleipner gas field as prime example of the CCS technology application

The Sleipner gas field is located 250 kilometres offshore west of Stavanger, Norway in the North Sea. The field was discovered in 1974. Two parts of the field are in production, Sleipner West (proven in 1974), and Sleipner East (1981). Production from the Sleipner West started in August 1996 and production from the Sleipner East in August 1993. [19]

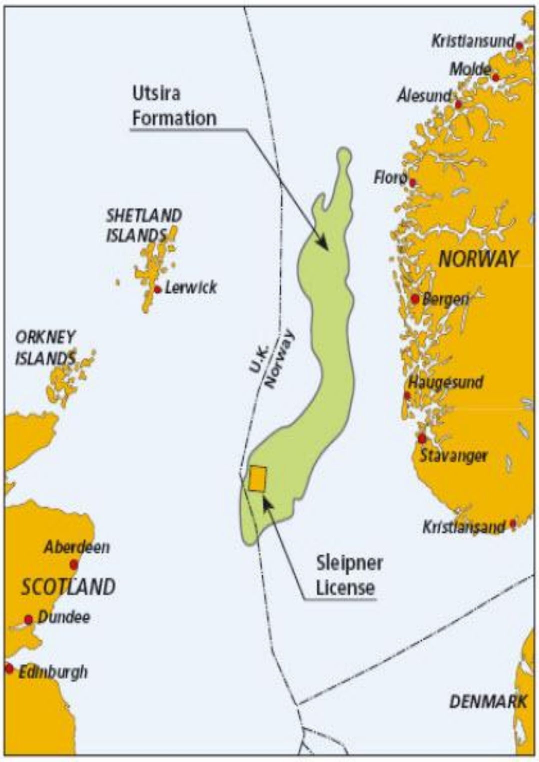

Fig. 3.4. Location of the Sleipner gas field [20]

The field is operated by Statoil (58.35 percent and operator), ExxonMobil E&P Norway (17.24 percent), Lotos E&P Norway AS (15 percent) and Total E&P Norge (9.41 percent). Proven reserves include 51.6 billion cubic metres of natural gas, 4.4 million tonnes of natural gas liquid, and 3.9 million cubic metres of condensates. The field produces natural gas and light oil condensates from sandstone structures about 2500 metres below sea level. Current production of natural gas is almost 36 million cubic metres of natural gas per day, and 14000 cubic metres of condensate per day. Total production rates of oil equivalent during all the time of exploration of the Sleipner gas field is presented in Figure 3.5. [20]

The Sleipner gas field consists of the following installations:

- Sleipner A – processing, drilling, and living quarter platform;
- Sleipner R – riser platform for gas and condensate export;
- Sleipner T – processing and carbon dioxide removal platform;
- Sleipner B – unmanned production platform. [21]

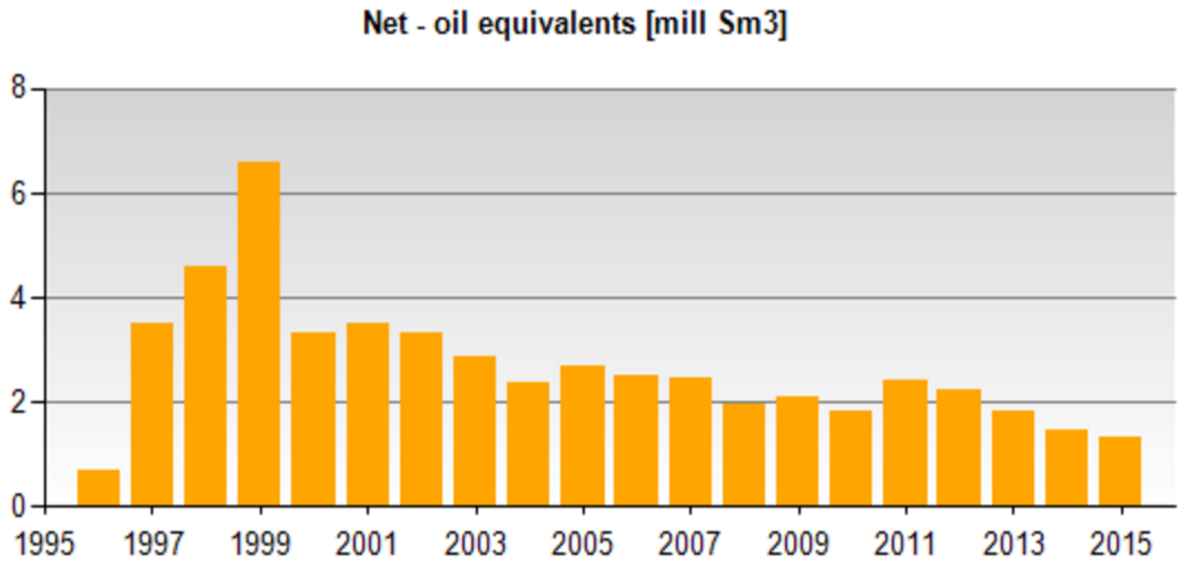

Fig. 3.5. Total production of Sleipner gas field in oil equivalent

The Sleipner A platform is located on the Sleipner East field as well as Sleipner R platform, and Sleipner B platform is located on the Sleipner West. The Sleipner B platform is operated remotely from the Sleipner A platform. To operate, an umbilical cable is used. Sleipner A platform is connected to the Sleipner T platform by a bridge. In its turn, Sleipner T platform is linked to the wellhead of the Sleipner B platform with a 12.5 kilometre carbon dioxide flow line.

It is well known that natural gas presents a mixture of different components having contrasting properties. The natural gas consists of 90% of methane and other hydrocarbons usually. It may contain nitrogen, oxygen, carbon dioxide, sulphur components and regular water as well. Natural gas containing a small volume of such impurities can be used as fuel. However, high concentrations of different substances make combustion insecure and less effective.

The natural gas produced on the Sleipner gas field has an incredibly high concentration of carbon dioxide. It reaches 9%. However, customers who buy this gas, require less than 2.5% of the $CO_2$ content. Separating the carbon dioxide and other impurities from the gas flow does not represent a challenge. Absorption and adsorption technologies are used widely and have a high level of development. Besides, there are many other technologies for flow division.

The main parameters and additional data related to carbon dioxide capture and storage are presented in Table 3.2. [21]

The main issue, in this case, is answering questions about recycling separated components and carbon dioxide particularly. As it was mentioned, emissions of carbon dioxide lead to global climate change. The Norwegian government has imposed a tax to stimulate companies to reduce $CO_2$ emissions. The tax started at a high rate of US$51 per tonne of $CO_2$. Nowadays, the tax reaches the mark of US$65. [22]

Because of this, there are several reasons for Statoil (as the main operator) to implement the technology of capture and storage:

- European market specification cap of 2.5 percent $CO_2$ for natural gas;
- The introduction of a Norwegian carbon dioxide tax on the offshore petroleum sector;
- Commitment to sustainable energy production. [23]

The technology of capture and storage of carbon dioxide in the Sleipner gas field is a first world experience. That is why all the oil and gas companies are interested in the success of this project. Nevertheless, there are a lot of questions related to this technology. Scientists want to define how carbon dioxide moves under the surface. The most important question is the probability of leakages of $CO_2$ to the atmosphere again. More detailed and accurate information about this technology is presented further.

Table 3.2. Main parameters of Sleipner $CO_2$ storage project

| Parameters | Description |
|---|---|
| Location | Offshore Norway, Central North Sea |
| | $CO_2$ capture source: natural gas from the Sleipner West field, via processing facility on the Sleipner T platform, 240 km west – south-west of Stavanger, offshore Norway |
| | $CO_2$ storage site: Utsira formation, above the Sleipner East field, Central North sea |
| Industry | Natural gas processing |
| $CO_2$ capture capacity volume | 0.85 million tonnes per annum (Mtpa) |
| Capture type | Pre-combustion capture (natural gas separation) |
| Capture method | Absorption chemical solvent – based process (Amine) |
| $CO_2$ capture start date | September 1996 |
| Primary storage option | Dedicated geological storage – offshore deep saline formation |
| Storage formation and depth | Sandstone at a depth approximately 800 – 1100 metres below sea level |
| Transportation type | No transport required (direct injection) |
| Transportation distance to storage site | Not applicable |

As it was mentioned, the Sleipner CO2 storage project is the first world experience. The injection rate of almost one million tonnes per annum makes this demonstration one of the largest in the world. This allows to consider it, as unique. The technology of capture and storage of carbon dioxide used in the Sleipner gas field is presented in Figure 3.6.

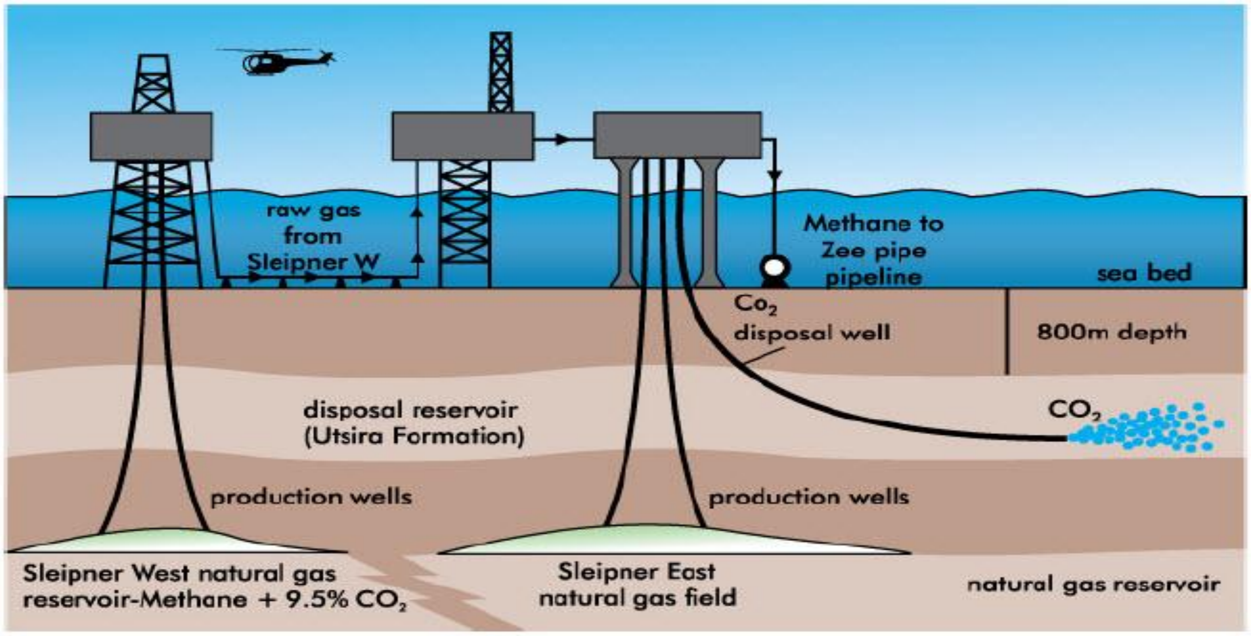

Fig. 3.6. Schematic depiction of the Sleipner West development [24]

According to this scheme, extracted natural gas from the Sleipner West field with a high concentration of carbon dioxide is transported to the processing and carbon dioxide removal in the Sleipner T platform.

Separation of components is carried out by the conventional amine based process. Methyl diethanolamine (MDEA) is used as a solvent. [25]

The treated gas is then piped to market via Sleipner A platform. Further gas is transported to Europe through the Zeepipe and Statpipe system as well as gas from the Troll field. Some of the gas is reinjected into the Sleipner East producing formation to improve condensate production. [26]

Unstabilised condensate is routed to Karstø north of Stavanger for processing. Here the stabilising process of condensate and natural gas liquids is carried out for on-shipping. [23]

The captured carbon dioxide is compressed and until then, it is piped to the Sleipner A platform. During the compression, $CO_2$ is converted to a supercritical state. The compression pressure reaches up to 8 MPa and, the temperature of the flow cools to approximately 40 °C. To obtain such conditions, a compressor train is used. It consists of four units, each with a fluid knockout drum to remove water, compressor, cooler and gas turbine driver.

After the compression, $CO_2$ flow in the supercritical state is injected via an injection well into the Utsira Formation. The Utsira formation has very favourable geological characteristics that are presented in Table 3.3. [24]

Table 7. Utsira formation characteristics

| Parameter | Value |
|---|---|
| Thickness, m | 50 – 250 |
| Permeability, Darcy | 1 – 10 |
| Porosity, % | > 30 % |
| Thickness of gas – tight cap rock, m | 700 |

Such properties of the Utsira Formation mean that the capacity of the reservoir is quite high. In practice, very few reservoirs have such auspicious characteristics.

One horizontal injection well is used to inject up to 1 Mtpa of $CO_2$ into the storage reservoir. The purity of the injected carbon dioxide flow is at 98 percent. The remaining 2 percent is mostly methane. This once again underlines the necessity to improve technologies in spite of its high quality. [23]

Approximately 16.5 million tonnes of carbon dioxide have been already injected since the implementation of the technology nowadays. According to the initial development plans for Sleipner West, the amount of $CO_2$ to be injected over 25 years (field's expected life) is about 25 million tonnes. But, due to decreasing production profile in the field and, therefore, decreasing carbon dioxide quantity, the revised amount to be injected is around 17.5 million tonnes by 2020.

One of the main issues that should be considered during the realisation of the technology of capture and storage of carbon dioxide is monitoring and modelling the distribution of injected $CO_2$. An extensive program in the Utsira Formation has been undertaken by several organisations. The following surveys are included in this program:

- Baseline 3D seismic survey;
- Eight-time lapse 4D seismic surveys;
- Four seabed micro gravimetric surveys;
- One electromagnetic survey;
- Two seabeds imagining survey. [23]

Each of these methods has its advantages and disadvantages. All of them have various strengths and benefits. That is why it is necessary to apply them together to obtain more accurate results and information about the distribution of injected carbon dioxide. Insufficiency in surveys and methods of the survey could cause serious consequences. The most possible are leakages.

# Chapter 4. Continental shelf of Russian Federation. Kirinskoye gas condensate field

This chapter is devoted to the application analysis of the technology of capture and storage of carbon dioxide on Russian offshore.

Russian continental shelf represents about 21% of the world shelf (more than 6 million km$^2$). Moreover, the most promising and available from the drilling point of view shelf exceeds 60% of its total flat zone. The high hydrocarbon potential of the Russian shelf is widely accepted. Total recoverable resources are estimated at more than 100 billion tonnes of oil equivalent within 80% of natural gas. [27]

Offshore oil and gas field development is still in its incipient state in Russia. More than 20 large petroleum-bearing basins have been already explored. 32 oil and gas fields have been discovered, including unique fields such as Shtokman gas condensate field, Rusanovskoye gas field, Leningradskoye gas field and others. Distribution analysis of the total initial resources shows that 67% is accounted for Western Arctic Seas by the majority. [28]

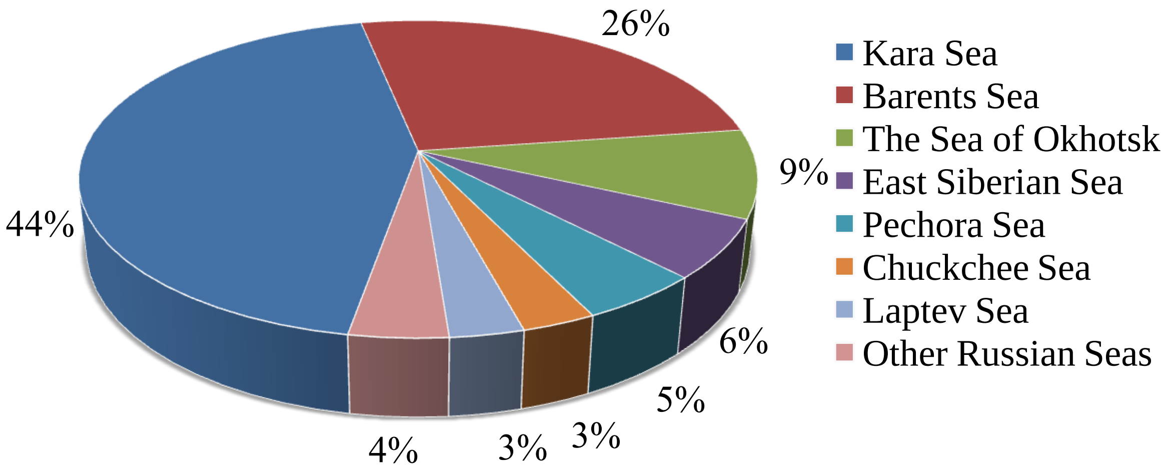

Fig. 4.1. Total initial resources distribution over the Russian continental shelf [29]

The biggest part of the discovered hydrocarbon resources (about 85%) is located in Kara Sea, Barents Sea, the Sea of Okhotsk and the Pechora Sea. So, on the Kara Sea shelf, including Tar Bay and the Gulf of Ob, 12 fields have been discovered: one oil field – Pobeda, two oil/gas condensate fields – Salekapskoye and Yurhanovskoye, two gas condensate fields – Leningradskoye and Rusanovskoye, and seven gas fields – Antipayutinskoye, Gugor'yahinskoye, Kamennomiskoye more, Obskoye, Tota-Yahinskoye, Severo-Kamennomiskoye and Semakovskoye. The Barents Sea and Pechora Sea shelves include 11 fields: four oil fields – Varandey-more, Dolginskoye, Medinskoye more and Prirazlomnoye, one oil/gas condensate field – Severo-Gulyaevskoye, three gas condensate fields – Ledovoye, Pomorskoye and Shtokman, and three gas fields – Ludlovskoye, Murmanskoye, and Severo-Kil'dinskoye. [30]

Forecast hydrocarbon resources of the Sea of Okhotsk are estimated at 6.56 BTOE. Discovered reserves are more than 4 billion tonnes. The best-known fields are located near the Sakhalin Island.

From the Figure 4.2 below, we can see that Sakhalin area includes seventeen different oil and gas basins. They are Shantarskiy, Kuhtuiskiy, Magadanskiy, Zapadno-Kamchatskiy, Gijiginskiy, Tinrovskiy, Severo-Sakhalinskiy, Deryuginskiy, Pogranichniy, Yujno-Sakhalinskiy, Zapadno-Sakhalinskiy, Vostochno-Deryuginskiy, Yujno-Okhotskiy, Continental slope, Severno-Kurilskiy, Sredinno-Kurilskiy, Yujno-Kurilskiy. [30]

Exploration near the Sakhalin Island began in the 1970s. Seven large fields (six oil/gas condensate and one gas condensate) and a small gas field in the Tatar Strait were discovered by the end of the 1990s. Total reserves of natural gas of the Sakhalin shelf are estimated at 3.5 trillion m$^3$. Sakhalin shelf includes the development of nine different projects – Sakhalin 1-9. Only six of these projects are in the exploration stage nowadays. Other projects are still at the initial steps. [30]

One of the biggest and the most potential project is Sakhalin-3. Forecast recoverable resources exceed 700 million tonnes of oil and 1.3 trillion of natural gas.

The project consists of four field blocks: Kirinskiy, Vostochno-Odoptinskiy, Aiyashskiy and Veninskiy.

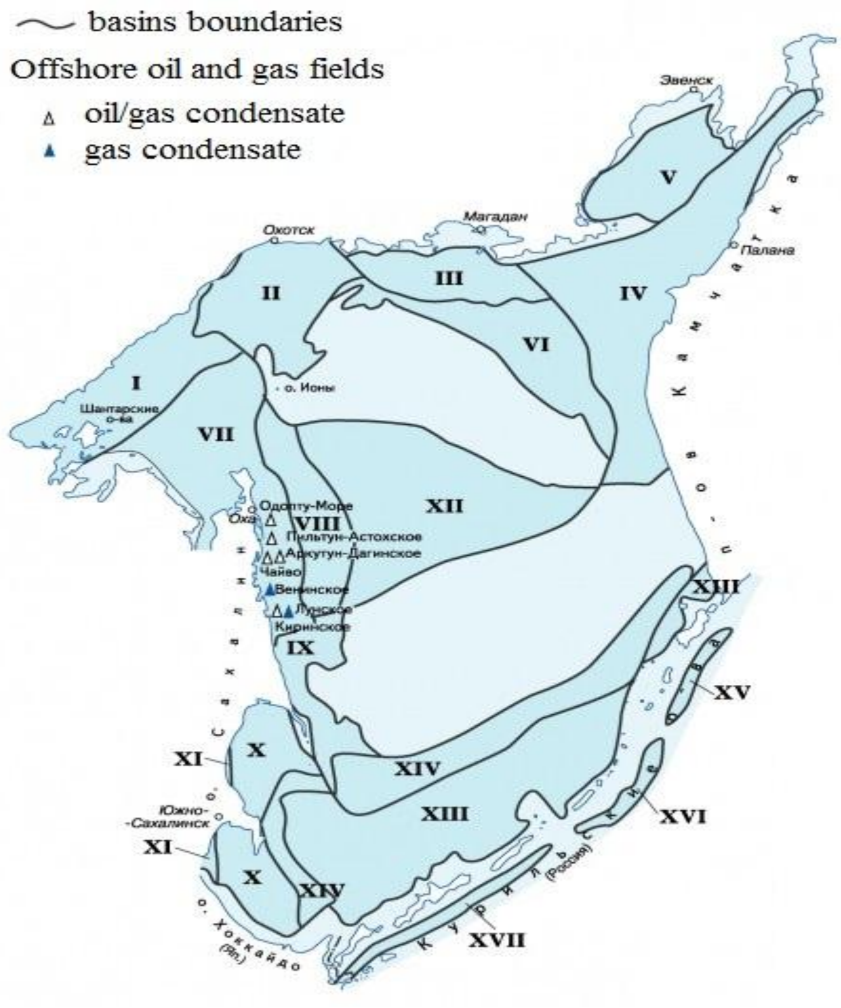

Fig. 4.2. Sakhalin oil and gas basins [30]

Table 4.1. Forecast resources of the Sakhalin-3 project blocks

| Block | Oil and condensate, million tonnes | Natural gas, billion $m^3$ |
|---|---|---|
| Kirinskiy | 453 | 720 |
| Vostochno-Odoptinskiy | 70 | 30 |
| Aiyashskiy | 97 | 37 |
| Veninskiy | 88 | 578 |

As it is shown in Table 4.1, the biggest block of the Sakhalin-3 project is a Kirinskoye gas condensate field. Further research on the technology of capture and storage of carbon dioxide and its application analysis is fulfilled precisely in this field.

## 4.1. Geological-field description of the Kirinskoye gas condensate field

### 4.1.1. General description of the Kirinskoye gas condensate field [31]

The Kirinskoye gas and condensate field is located 28 kilometres offshore Sakhalin Island in the Sea of Okhotsk. The field was discovered in 1992, but development began only in October 2013 by "Gazprom" company. The development of the field belongs to the project "Sakhalin3". Proven reserves include 162 bcm of gas and 19.1 Mt of condensate. [32]

The wells were drilled by 6th generation drilling rigs from semi-submersible platforms. The depth of the wells is no less than 3000 m. Within the construction of infrastructure, 20 support vessels were used.

The depth of the water in the field area varies from 60 to 100 m. [33]

Maximum 100-year storm wave height (hmax) is 18 m and the significant wave height (hs) is 2 m. In December and January, the weather is the most severe, 13-16 m wave height and 30-40 km/h wind may occur. The maximum period of the waves at that time could be up to 13 sec. The velocity of the currents in the area of the Kirinskoye field is about 3 m/h. Storms duration is 6-8 days per month. The average temperature of the sea is about 9 $^{0}$C, but on the seabed, it is about 2 $^{0}$C below zero.

The most challenging environmental load in that area is ice. The area is a part of the Arctic region, with up to seven months of ice cover per year, from November till May.  At the end of December, the third area of the Sea of Okhotsk is covered with ice. During the severe winter, the whole sea is covered with 0.8-2 m thick ice. [34]

Additional data about climate conditions of the Sakhalin region is presented in Table 4.2-4.3. The region review scheme of the work is presented in Figure 4.3. [35]

Table 4.2. Climatic parameters of the warm period of the year for hydrometeorological station “Nogliki”

| Parameter | SNiP 23-01-99 |
|---|---|
| Atmospheric pressure, gPa | 1010 |
| Air temperature, $^0$C with a frequency of 0.95 | 17 |
| Air temperature, $^0$C with a frequency of 0.98 | 21.4 |
| Average maximum temperature of the warmest month, $^0$C | 19.4 |
| Absolute maximum temperature, $^0$C | 37 |
| The average daily amplitude of air temperature of the warmest month, $^0$C | 9.2 |
| The average monthly relative humidity of the warmest month, % | 85 |
| Average monthly relative humidity in the 15 hours of the warmest month, % | 72 |
| The amount of precipitation in April-October, mm | 481 |
| The daily maximum precipitation, mm | 87 |
| Prevailing wind direction in June-August | SW |
| The minimum average wind speeds at compass point July, m/s | - |

Table 4.3. Climatic parameters of the cold period of the year for hydrometeorological station “Nogliki”

| Parameter | | | SNiP 23-01-99 |
|---|---|---|---|
| The temperature of the coldest days, °C, with frequency | 0.98 | | -36 |
| | 0.92 | | -35 |
| The temperature of the coldest five-day week, ° C, with frequency | 0.98 | | -33 |
| | 0.92 | | -32 |
| Air temperature, °C, with frequency 0,94 | | | -25 |
| Absolute minimum air temperature, ° C | | | -48 |
| The average daily amplitude of air temperature of the coldest month, °C | | | -10.3 |
| Duration, per day, and the average air temperature, °C, the period from the average daily air temperature | ≤ 0 °C | duration | 187 |
| | | average temperature | -11.7 |
| | ≤ 8 °C | duration | 260 |
| | | average temperature | -7.2 |
| | ≤ 10 °C | duration | 281 |
| | | average temperature | -6 |
| The average monthly relative humidity of the coldest month, % | | | 76 |
| Average monthly relative humidity in the 15 hours of the coldest month, % | | | 69 |
| The amount of precipitation in November - March, mm | | | 140 |
| Prevailing wind direction in December - February | | | NW |
| The maximum of the average wind speed rhumbs January, m/s | | | - |
| Average wind speed, m/s, during the period from the average daily temperature ≤ 8 °C | | | 4.2 |

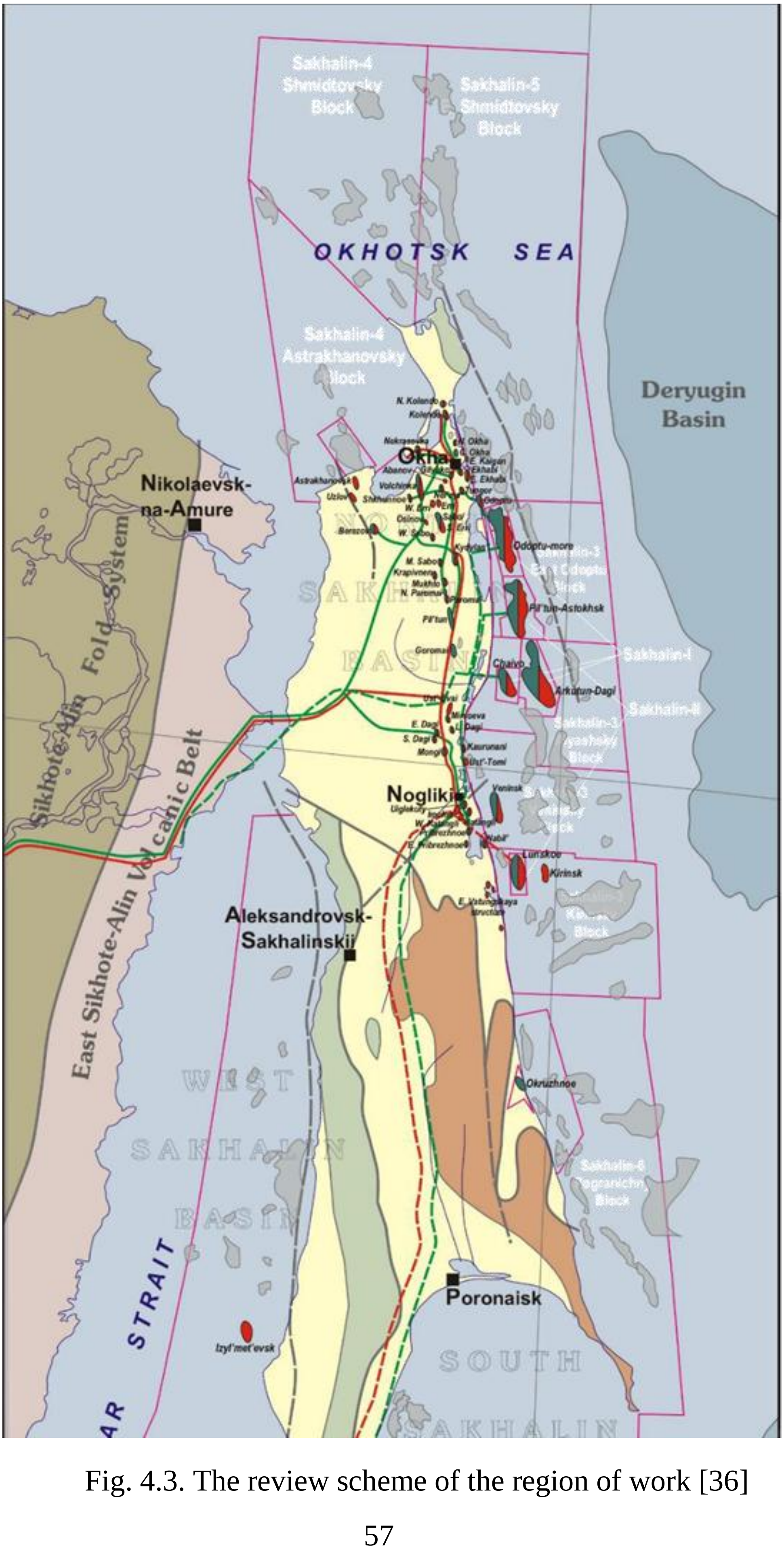

Fig. 4.3. The review scheme of the region of work [36]

### 4.1.2. Geological characteristic of the region of work

Sakhalin Island belongs to the Sakhalin-Hokkaidskaya crumpled system. This system consists of three megazones: Western, Central and Eastern. From the tectonic point of view, the structure of the Sakhalin Island includes three structural layers: the lower – Paleozoic-Upper Cretaceous, the middle – Upper Cretaceous, the upper – Cenozoic. The upper structural layer is the one bearing oil and gas. It is represented by sandy-argillaceous rocks that include more than 20 sandy layers. It is typical for such kind of formation complex to have an accumulation of oil and gas.

First official data about the hydrocarbon potential of the Sakhalin Island was published in 1880. More than 69 oil, gas and condensate fields are developed in the Sakhalin Island and on its shelf nowadays. Almost all of the fields are located in the northeastern part of the island and belong to the structural high of the Western megazone. Asymmetric geology aspects with cragged east legs and flat-lying west legs characterise the rock bends.

Essentially all oil and gas fields of the Sakhalin Island are multi-layers reservoirs that are significantly characterised by the activity of the tectonic fissures. The majority of the reservoirs is a fault-bounded and roof deposits.

The sedimentary mantle of the Kirinsky block consists of the Paleocene, Neocene and quaternary rocks. The Paleocene assemblage includes Oligocene sediments that consist of machegarsky and daekhuri horizons. Clays, argillites, and silt form the machegarsky horizon. The Daekhuri horizon spreads almost over the whole northern part of the Sakhalin Island and consists of the argillaceous-siliceous rocks.

The Neocene assemblage includes the Uinin, Dagi, Okobykay, Nutovo, and Pomyrsky horizons.

The quaternary system consists of gravel, grit and sand with a broken shell.

The Kirinsky block corresponds to both: the Niysky anticline zone and Mynginsky horst-anticline high. The main productive complex here is the sandy-clay formations of the Dagi horizon, which includes the accumulations of two giant fields – Lunskoye and Kirinskoye.

Table 4.4. Well stratigraphic sequence, attitude and cavernosity ration of the layers

| Stratification depth, m | | Geologic unit, formation | | | | Attitude by the bottom, degree | Cavernosity ratio |
|---|---|---|---|---|---|---|---|
| Top | Bottom | Name | | Subscript | | Angle | |
| 119 | 130 | The quaternary system | | Q | | 0 | 1.50 |
| 130 | 830 | The Neocene system. Pliocene. Pomyrsky horizon | | $N_2$ pm | | 0 | 1.35 |
| 830 | 1530 | The Neocene system. Miocene-Pliocene. Nutovo horizon | Upper Nutovo subhorizon | $N_{1-2}$ nt | $N_2$ $nt_2$ | 2 | 1.30 |
| 1530 | 2230 | | Lower Nutovo sudhorizon | | $N_1$ $nt_1$ | 2 | 1.20 |
| 2230 | 2911 | The Neocene system. Miocene. Okobykay horizon | | $N_1$ ok | | 2 | 1.38 |
| 2911 | 2970 | The Neocene system. Miocene. Dagi horizon | | $N_1$ dg | | 2-5 | 1.30 |

Table 4.5. Well sequence lithological character

| Subscript | Stratification depth, m | | Rock | |
|---|---|---|---|---|
| | Top | Bottom | Name | Percentage |
| $Q – N_2$ pm | 119 | 830 | silt, gravel | 4 |
| | | | sands | 30 |
| | | | clays | 65 |
| | | | aleurolite | 1 |
| $N_2$ $nt_2$ | 830 | 1530 | aleurolite | 9 |
| | | | sandstones | 10 |
| | | | clays | 80 |
| | | | limestones | 1 |
| $N_1$ $nt_1$ | 1530 | 2230 | aleurolite | 20 |
| | | | sandstones | 10 |
| | | | clays | 70 |
| $N_1$ ok | 2230 | 2911 | clays | 65 |
| | | | sandstones | 20 |
| | | | aleurolite | 15 |
| $N_1$ dg | 2911 | 2970 | sandstones | 90 |
| | | | aleurolite | 5 |
| | | | clays | 5 |

Table 4.6. Physical and mechanical properties of the rock along the well sequence

| Subscript | Stratification depth, m | | Name of the rock | Density, kg/$m^3$ | Porosity, % | Permeability, millidarcy | Clay content, % | Carbonate content, % | Hardness, MPa | Category of abrasibility | Poison's ratio | Hydration deconsolidation of the rock |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Top | Bottom | | | | | | | | | | |
| $Q – N_2$ pm | 119 | 830 | Silt, gravel, sands, clays, aleurolite | 1980 – 2270 | * | * | * | * | 150 – 550 | 4 – 5 | * | * |
| $N_{1-2}$ nt | 830 | 2230 | Aleurolite, sandstones, clays | 2200 | * | <250 | 10 – 90 | * | 150 – 750 | 4 – 5 | 0.13 – 0.45 | 0.05 – 0.14 |
| $N_1$ ok | 2230 | 2911 | Clays, aleurolite, sandstones | 2300 | * | * | 40 – 70 | * | 150 – 750 | 4 – 5 | 0.25 – 0.35 | 0.13 – 0.14 |
| $N_1$ dg | 2911 | 2970 | Sandstones, aleurolite, clays | 2300 | 19 - 23 | 199 - 242 | 5 - 90 | 1 - 6 | 500 – 980 | 4 – 5 | 0.25 – 0.35 | 0.1 – 0.135 |

*- unknown parameters. Depth is measured starting from the rotary table. The distance between the rotary table and the seabed is equal to 119 m. Sea depth is 88 m.

Table 4.7. Pressure and temperature distribution along the well sequence

| Subscript | Stratification depth, m | | Pressure gradient, MPa/m | | | | | | | | Temperature at the end of the interval, $^0$C |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Top | Bottom | Formation pressure | | Pore pressure | | Hydrofracturing pressure | | Geostatic pressure | | |
| | | | Top | Bottom | Top | Bottom | Top | Bottom | Top | Bottom | |
| Q | 119 | 130 | 0.0074 | 0.0076 | 0.0074 | 0.0076 | 0.0074 | 0.0103 | 0.0074 | 0.0107 | - |
| $N_2$ pm | 130 | 830 | 0.0076 | 0.0096 | 0.0076 | 0.0096 | 0.0103 | 0.0140 | 0.0107 | 0.0181 | 24.8 |
| $N_{1-2}$ nt | 830 | 1140 | 0.0096 | 0.0097 | 0.0096 | 0.0097 | 0.0140 | 0.0147 | 0.0181 | 0.0186 | 40.9 |
| - | 1140 | 2230 | 0.0097 | 0.0099 | 0.0097 | 0.0099 | 0.0147 | 0.0151 | 0.0186 | 0.0193 | 77.4 |
| $N_1$ ok | 2230 | 2335 | 0.0099 | 0.0099 | 0.0099 | 0.0099 | 0.0151 | 0.0152 | 0.0193 | 0.0195 | 81.4 |
| - | 2335 | 2911 | 0.0099 | 0.0099 | 0.0099 | 0.0099 | 0.0152 | 0.0155 | 0.0195 | 0.0203 | 102.6 |
| $N_1$ dg | 2911 | 2970 | 0.0101 | 0.0101 | 0.0101 | 0.0101 | 0.0155 | 0.0155 | 0.0203 | 0.0204 | 105.2 |

### 4.1.3. Gas and condensate compositions and reserves

Oil and condensate of the Sakhalin Island northeastern part possess a differential characteristic – low sulphur concentration. As for natural gas, it is necessary to pay attention to the fact of absence of hydrogen disulphide that confines these deposits of hydrocarbons to the terrigenous sediments. [37]

Gases are methane and sweet. The natural gas composition is presented in Table 4.8. [38]

Table 4.8. Sakhalin Island deposits natural gas composition

| Component | Content, % |
|---|---|
| Methane | 86.34 – 87.1 |
| Ethane | 3.77 – 3.86 |
| Propane | 1.85 – 2.03 |
| Butane | 0.87 – 1.14 |
| Pentane | 0.22 – 0.29 |
| Nitrogen | 0.15 – 0.19 |
| Carbon dioxide | 2.89 – 3.10 |

The high promising content of the combustible fraction characterises the condensate of the Sakhalin Island deposits. Therefore, the yield of NK-120 $^0$C gasoline fraction varies from 30.8 % to 34.8 % of the mass, the yield of NK-180 $^0$C gasoline fraction changes between 54.7 – 61.5 % of the mass, the yield of 120-230 $^0$C kerosene cut is about 38.3 – 40.8 % of the mass, the yield of 150-280 $^0$C kerosene cut is 35.4 – 37.5 % of the mass, the yield of 140-320 $^0$C diesel fraction is 47.3 – 49.5 %. Condensates are similar in hydrocarbon-type content of distillate fraction that boils out before 300 $^0$C. The high content of the aromatic hydrocarbons is typical for all condensates.

Within the boundaries of the Kirinsky block, three gas condensate fields were discovered: Kirinskoye, Yuzhno-Kirinskoye, and Mynginskoye.

Gas and condensate reserves of the Kirinskoye field are booked reserves by category $C_1$ according to the protocol of the session of the State Committee for Mineral Reserves Rosnedra №2787-DSP by 01.06.2012.

Yuzhno-Kirinskoye field is explored by two exploratory wells. After interpretation of the exploratory drilling and 3D seismic results, estimation of gas and condensate reserves was done. Reserves by category $C_1$ and $C_2$ are booked reserves.

Mynginskoye field is explored by one well. The estimation of the reserves by category $C_1$ and $C_2$ was done as well.

Gas and condensate reserves of the listed fields are represented in Tables 4.9 and 4.10.

Table 4.9. Gas reserves (SRC booked reserves) of the Kirinsky block

| Field | SRC booked reserves, billion $m^3$ | | |
|---|---|---|---|
| | Category $C_1$ | Category $C_2$ | Category $C_1 + C_2$ |
| Kirinskoye | 162.503 | - | 162.503 |
| Yuzhno-Kirinskoye | 160.902 | 403.088 | 563.990 |
| Myginskoye | 5.712 | 14.142 | 19.854 |
| Total | 329.117 | 417.23 | 746.347 |

Table 4.10. Condensate reserves (SRC booked reserves) of the Kirinsky block

| Field | SRC booked reserves, million tonnes | | |
|---|---|---|---|
| | Category $C_1$ | Category $C_2$ | Category $C_1 + C_2$ |
| Kirinskoye | 19.136 | - | 19.136 |
| Yuzhno-Kirinskoye | 20.453 | 51.239 | 71.692 |
| Myginskoye | 0.726 | 1.798 | 2.524 |
| Total | 40.315 | 53.037 | 93.352 |

### 4.1.4. Engineering parameters of the Kirinskoye field development plan

The Kirinskoye field was discovered in 1992. Two exploratory wells were drilled in the beginning of 2010. The gas and condensate inflows were obtained with the flow rate of 520 000 $m^3$/d and 70 $m^3$/d respectively during the well testing. The field was not put into production. "The development plan of the Kirinskoye gas condensate field" was fulfilled by OOO «Gazprom VNIIGAZ» (protocol of confirmation №10-p/2010 by 09.04.2010).

Reservoir management is planning to conduct with three stages.

During the first stage, well re-entry and start-up operations of the well №2 (northern part of the field) and the well №3 (southern part of the field) are implemented. Both wells are converted to the production well stock. Further, two exploitation wells are drilled in the most productive northern part of the central reservoir land.

During the second stage, the northern part of the central reservoir land is placed on stream. Two exploitation wells are drilled in the south of the central part.

During the third stage, it is designed to obtain the planned production level of the natural gas. [39]

## 4.2. Subsea concept of the Kirinskoye gas condensate field

The design solutions for the field development and construction facilities in the Kirinskoye license block area of Sakhalin-3 are based on three principal factors, namely seasonal ice conditions, water depth and distance to shore facilities. [40]

For the Kirinskoye gas and condensate field development six production wells have been drilled (nowadays the question about extra well is under consideration). The Subsea production system (SPS) includes the subsea manifold, infield pipelines with gas gathering system, supplying monoethylene glycol pipeline and armoured electro hydraulic umbilical laid along the seabed. The handling of the subsea production system goes through the signals from the onshore control room.

Gas and condensate mixture that comes from the wells goes through the gathering pipelines into the manifold. All flows are combined into one and move through the 28 km flowline to the onshore processing facility (OPF). Treated gas is transported to the main compressor station “Sakhalin” and then to the trunk pipeline “Sakhalin-Khabarovsk-Vladivostok”. [41]

In order to prevent hydrate formation inside the flowline, the process of monoethylene glycol (MEG) injection is implemented. Farther MEG is going to be separated from the flow at the onshore processing facility and re-injected. Illustration of the subsea production system is given in Figure 4.4. [31]

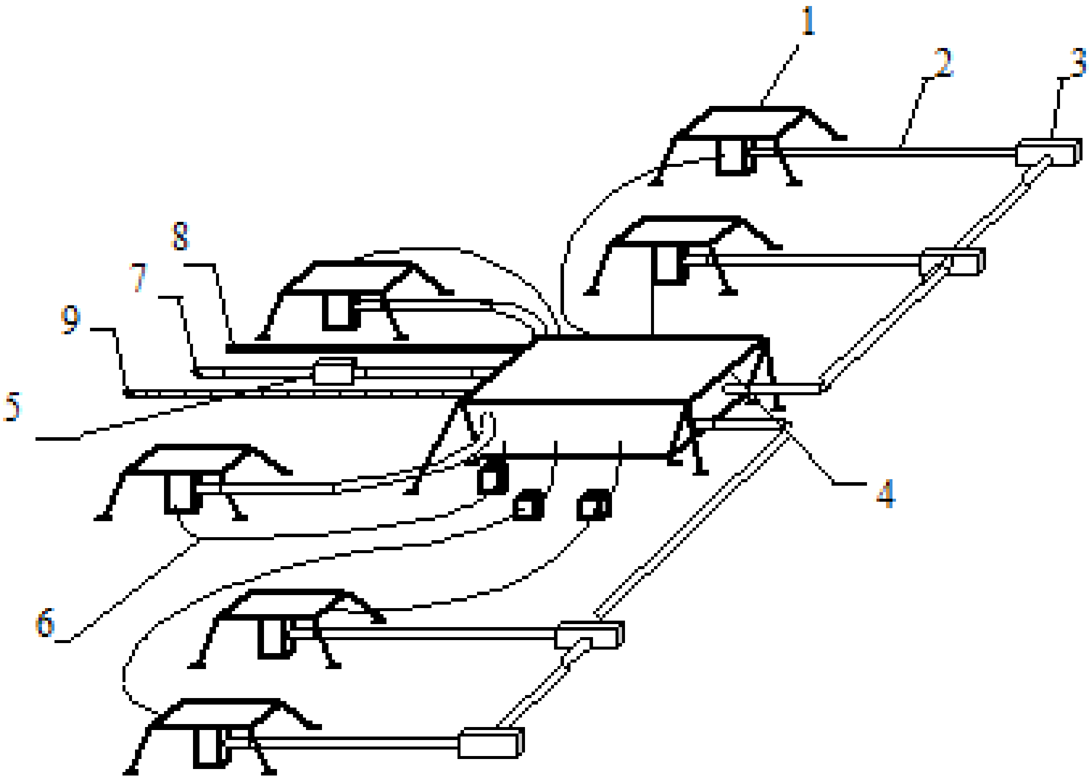

Fig. 4.4. SPS Layout in the Kirinskoye Field [31]

SPS is presented as cluster layout. A fluid produced from the well flows through the horizontal X-mas tree 1 (HXT) and gathering pipeline 2 to the terminal unit 3. The pipeline 2 and terminal unit 3 is designed for connecting the outmost wells to a line connected to the manifold 4. The pipeline 7 and pipeline end termination 5 are used as connectors of the manifold 4 with the onshore processing facility. The whole SPS is controlled from the control site located onshore. The main armoured electro-hydraulic umbilical 9 is laid upon the seabed and connects the manifold with the SPS control site. The transmitted command comes from the shore to the manifold, and then this signal goes through the intrafield umbilical 6 to the X-mas tree. During production, special pipeline 8 provides SPS with monoethylene glycol.

The soil of the seabed resulted in lots of problems in the subsea infrastructure installation. The oozy bottom had to be replaced in order to prevent movement of templates and further unexpected challenges. The muddy bottom under the manifold was removed and created ditch was filled with 96 tonnes of gravel.

### 4.2.1. Special technological features of the Kirinskoye gas condensate field subsea concept

Related to the subsea facilities in this field, two main features are special.

*Manifold*

Gas from the wells is supplied to the manifold (gathering station). The manifold is formed by several pipelines mounted upon a single foundation and designed to accommodate high pressure and be connected according to a certain pattern. The manifold distributes the gas flows, monoethylene glycol flow, chemicals and control signals transmitted to the subsea production facilities. The manifold includes connection points for tie-in of the flowline and umbilical back to the host facility. The manifold has the following characteristics: designed pressure 25 MPa; designed flowlines pressure 34.5 MPa; weight 220 tonnes; dimensions – 27.5×13×4.9 m.

*Subsea Trees*

Wellheads of all six wells are equipped with horizontal X-mas tree and well protection equipment. In horizontal subsea tree systems, the tree is installed on the wellhead and then the tubing hanger is installed inside the tree. The HXT consists of a valve block with bores and valves configured in such a manner that fluid flow and pressure from the well can be controlled for both safety and operational purposes. The tree includes a connector for attachment to the wellhead. The full-bore aspect of the HXT design obviously does not allow vertical bore valves on the X-mas tree (XT), so HXTs are configured with the valve bores located horizontally within the tree body. This allows the XT to be equipped with a production bore larger than that normally allowed in a vertical XT. Current HXT has the following dimensions – 5.1×3.9×4.4 m, mass – 51 tonnes and it can withstand: - Pressure of section isolation valves: up to 100 MPa; - Pressure of control line: up to 65 MPa. The trawl protection construction secures the X-mas tree from a mechanical impact. Protection equipment has mass – 90 tonnes and the following dimensions – 23×23×10 m.

# Chapter 5. Application analysis of the CCS technology on Russian shelf

This chapter of the master's thesis is devoted to the application analysis of the technology of capture and storage of carbon dioxide on Russian shelf. Two key features were analysed: availability of the technological design of the Kirinskoye gas condensate field and characteristics of the hosted formation.

The main highly corrosive component of the produced natural gas from Kirinskoye field is carbon dioxide. According to the forecast data (Table 5.1), $CO_2$ content is 2.77 % at the beginning of the field development, 2.804 % as of the 16th year of development, and 2.793 % at the end of the development. The second aggressive component is moisture. Due to the existence of the condensation moisture, the electrochemical mechanism of the carbon dioxide corrosion happens to be. The forecast shows (Table 5.2) that during the development of the field the amount of producing water will increase including condensation moisture and reservoir water. [42]

According to the memorandum "Kirinskoye gas condensate field development. Chapter 6. Marine development design" the petroleum-bearing formation is characterised by:

- Initial formation pressure up to 29.5 MPa;
- Initial formation temperature up to 115 $^{o}$C;
- Initial calculated pressure on different parts of the field is 24-25.5 MPa;
- Maximum calculated temperature on different parts of the field is about 15-90 $^{o}$C;
- Initial static pressure during closed wellhead of the well is 24 MPa;
- The maximum temperature of the open wellhead is 90 $^{o}$C. [43]

Table 5.1. A forecast of the natural gas composition of the Kirinskoye gas condensate field (wellhead temperature is equal 88 $^{o}$C)

| Year | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $N_2$ | 0.160 | 0.160 | 0.161 | 0.161 | 0.161 | 0.162 | 0.162 | 0.162 | 0.163 | 0.163 | 0.163 | 0.163 | 0.163 | 0.163 | 0.163 |
| $CO_2$ | 2.770 | 2.770 | 2.773 | 2.776 | 2.778 | 2.782 | 2.785 | 2.788 | 2.790 | 2.793 | 2.795 | 2.797 | 2.799 | 2.801 | 2.803 |
| $CH_4$ | 87.730 | 87.730 | 87.955 | 88.179 | 88.275 | 88.484 | 88.624 | 88.736 | 88.854 | 88.911 | 88.977 | 89.031 | 89.074 | 89.099 | 89.102 |
| $C_2H_6$ | 3.380 | 3.380 | 3.379 | 3.378 | 3.378 | 3.379 | 3.380 | 3.382 | 3.354 | 3.386 | 3.388 | 3.391 | 3.395 | 3.398 | 3.402 |
| $C_3H_8$ | 1.650 | 1.650 | 1.644 | 1.638 | 1.635 | 1.630 | 1.628 | 1.626 | 1.625 | 1.625 | 1.625 | 1.626 | 1.628 | 1.631 | 1.635 |
| $C_4H_{10}$ | 0.930 | 0.930 | 0.922 | 0.925 | 0.911 | 0.904 | 0.900 | 0.896 | 0.893 | 0.892 | 0.891 | 0.891 | 0.891 | 0.893 | 0.896 |
| $C_{5+}$ | 3.380 | 3.380 | 3.167 | 2.952 | 2.861 | 2.660 | 2.521 | 2.410 | 2.310 | 2.230 | 2.161 | 2.064 | 2.049 | 2.014 | 1.999 |
| Year | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 |
| $N_2$ | 0.163 | 0.163 | 0.162 | 0.162 | 0.162 | 0.162 | 0.162 | 0.162 | 0.162 | 0.162 | 0.162 | 0.162 | 0.162 | 0.162 | 0.162 |
| $CO_2$ | 2.804 | 2.803 | 2.797 | 2.793 | 2.793 | 2.793 | 2.793 | 2.793 | 2.793 | 2.793 | 2.793 | 2.793 | 2.793 | 2.793 | 2.793 |
| $CH_4$ | 89.074 | 88.995 | 88.683 | 88.532 | 88.532 | 88.532 | 88.532 | 88.532 | 88.532 | 88.532 | 88.532 | 88.532 | 88.532 | 88.532 | 88.532 |
| $C_2H_6$ | 3.406 | 3.409 | 3.408 | 3.405 | 3.405 | 3.405 | 3.405 | 3.405 | 3.405 | 3.405 | 3.405 | 3.405 | 3.405 | 3.405 | 3.405 |
| $C_3H_8$ | 1.640 | 1.646 | 1.655 | 1.656 | 1.656 | 1.656 | 1.656 | 1.656 | 1.656 | 1.656 | 1.656 | 1.656 | 1.656 | 1.656 | 1.656 |
| $C_4H_{10}$ | 0.901 | 0.909 | 0.923 | 0.926 | 0.926 | 0.926 | 0.926 | 0.926 | 0.926 | 0.926 | 0.926 | 0.926 | 0.926 | 0.926 | 0.926 |
| $C_{5+}$ | 2.012 | 2.076 | 2.373 | 2.501 | 2.501 | 2.501 | 2.501 | 2.501 | 2.501 | 2.501 | 2.501 | 2.501 | 2.501 | 2.501 | 2.501 |

Table 5.2. Forecast data of the Kirinskoye gas condensate field development

| Year | Annual production, bln m$^3$ | Cumulative gas production, bln m$^3$ | Number of wells | Pressure, atm | | | Differential pressure drawdown, atm | Wellhead temperature, $^{o}$C |
|---|---|---|---|---|---|---|---|---|
| | | | | Average reservoir | Bottom hole | Wellhead | | |
| 1 | 0.47 | 0.5 | 2 | 293.9 | 276.0 | 212.6 | 11.5 | 84.6 |
| 2 | 1.90 | 2.4 | 4 | 287.3 | 272.1 | 208.4 | 9.9 | 85.2 |
| 3 | 3.39 | 5.8 | 6 | 275.7 | 259.6 | 197.5 | 10.6 | 85.2 |
| 4 | 4.25 | 10.0 | 6 | 261.9 | 244.0 | 184.7 | 10.7 | 84.8 |
| 5 | 4.25 | 14.3 | 6 | 249.2 | 229.6 | 173.6 | 11.7 | 84.6 |
| 6 | 4.25 | 18.5 | 6 | 237.5 | 216.0 | 163.1 | 13.0 | 84.3 |
| 7 | 4.25 | 22.8 | 6 | 226.3 | 203.4 | 153.4 | 13.9 | 84.0 |
| 8 | 4.18 | 26.9 | 6 | 215.4 | 191.6 | 144.3 | 14.3 | 83.7 |
| 9 | 4.14 | 31.1 | 6 | 204.6 | 180.0 | 135.2 | 14.8 | 83.3 |
| 10 | 3.99 | 35.1 | 6 | 194.2 | 168.8 | 126.2 | 15.4 | 82.8 |
| 11 | 3.98 | 39.0 | 6 | 183.8 | 157.3 | 116.7 | 16.2 | 82.4 |
| 12 | 3.95 | 43.0 | 6 | 173.5 | 145.2 | 106.6 | 17.5 | 81.8 |
| 13 | 3.56 | 46.5 | 5 | 164.2 | 137.6 | 100.5 | 16.9 | 82.2 |
| 14 | 3.20 | 49.7 | 5 | 155.8 | 128.6 | 92.7 | 17.4 | 81.3 |
| 15 | 3.19 | 52.9 | 5 | 147.3 | 119.4 | 84.5 | 18.0 | 80.9 |

Table 5.2. Forecast data of the Kirinskoye gas condensate field development (continue)

| Year | Annual production, bln $m^3$ | Cumulative gas production, bln $m^3$ | Number of wells | Pressure, atm | | | Differential pressure drawdown, atm | Wellhead temperature, °C |
|---|---|---|---|---|---|---|---|---|
| | | | | Average reservoir | Bottom hole | Wellhead | | |
| 16 | 3.17 | 56.1 | 5 | 138.7 | 109.8 | 75.5 | 18.7 | 80.3 |
| 17 | 3.10 | 59.2 | 5 | 130.4 | 100.4 | 66.1 | 19.5 | 79.4 |
| 18 | 3.08 | 62.3 | 5 | 121.9 | 90.2 | 54.6 | 20.6 | 78.3 |
| 19 | 3.05 | 65.3 | 5 | 113.3 | 80.9 | 44.4 | 21.0 | 77.4 |
| 20 | 2.88 | 68.2 | 5 | 105.2 | 72.9 | 38.1 | 20.6 | 77.0 |
| 21 | 2.67 | 70.9 | 5 | 97.5 | 66.2 | 34.8 | 19.8 | 77.1 |
| 22 | 2.46 | 73.3 | 5 | 90.4 | 60.0 | 31.9 | 19.1 | 77.1 |
| 23 | 1.96 | 75.3 | 4 | 84.7 | 57.6 | 31.2 | 18.4 | 77.9 |
| 24 | 1.79 | 77.1 | 4 | 79.5 | 53.0 | 27.6 | 18.2 | 77.4 |
| 25 | 1.71 | 78.8 | 4 | 74.4 | 48.7 | 23.8 | 17.9 | 77.2 |
| 26 | 1.57 | 80.4 | 3 | 69.7 | 46.4 | 21.4 | 17.5 | 78.9 |
| 27 | 1.19 | 81.6 | 3 | 66.1 | 43.1 | 20.1 | 17.2 | 77.3 |
| 28 | 1.03 | 82.6 | 3 | 63.1 | 41.3 | 20.0 | 16.6 | 76.5 |
| 29 | 0.97 | 83.6 | 3 | 60.2 | 39.2 | 20.0 | 15.9 | 76.4 |
| 30 | 0.94 | 84.5 | 3 | 57.3 | 37.4 | 20.0 | 14.9 | 76.6 |

The content of aggressive gases such as carbon dioxide could be described by the fractional or partial pressure. It could be estimated as:

$$P_{CO_2} = \frac{P * C_{CO_2}}{100} \tag{5.1}$$

where P – operating pressure, MPa or atm;

$C_{CO_2}$- the percentage of carbon dioxide in natural gas.

If the average content of carbon dioxide in the produced natural gas from the Kirinskoye field is equal to 2.8 %, and the initial reservoir pressure is equal to 29.5 MPa, then the fractional or partial pressure of carbon dioxide is equal to 0.83 MPa.

The following normative documents of OAO «Gazprom» specify methods for the determination of the corrosion activity of substances and metal protection from internal corrosion including the presence of carbon dioxide as well:

- «Gazprom» company standard 9.0-001-2009 “Corrosion protection. Highlights”;
- «Gazprom» company standard 9.3-011-2011 “Corrosion protection. Inhibitory corrosion protection of the field facilities and pipelines. Fundamental requirements”;
- «Gazprom» company standard 9.2-020-2012 “Corrosion protection. Corrosion protection of the field facilities and pipelines with the absence or small concentration of hydrogen disulphide”.

According to the listed standards, the following classification of corrosion severity was accepted:

- The fluids with a partial pressure of carbon dioxide over 0.2 MPa should be considered as corrosion aggressive and they require the treatment of special anticorrosion remedies and the appliance of the corrosion monitoring to control the effectiveness of protection measures;
- The fluids with a partial pressure of carbon dioxide in a range of 0.05-0.2 MPa should be considered as middle aggressive and require the corrosion monitoring appliance;

- The fluids with a partial pressure of carbon dioxide smaller than 0.05 MPa should be considered as low aggressive and do not require any special remedial measures.

The pre-cited classification of corrosion severity is tentative and allows evaluation of the corrosion behaviour. More accurate data could be obtained only through the evaluation of the corrosion velocity.

It is seen, that the exceedance of the maximum allowed value of the carbon dioxide fractional pressure is bigger than four times. Due to this fact, the fluids that are produced on the Kirinskoye field are potentially corrosion aggressive. It is necessary to pay attention to the multifactoriality of the carbon dioxide corrosion process. It means that changes of other parameters that influence on the corrosion velocity should be considered as well. These factors are water mineralisation, temperature rising, etc. [42]

The analysis of the projection data is presented both in Table 5.3 and in Figure 5.1. The analysis shows that the maximum $CO_2$ production will be in the 4th year of full field development and amounts to 0.216 million tonnes. Cumulative $CO_2$ production will be more than four million tonne towards the end of the field development. The obtained results show that the implementation of the technology of carbon dioxide is necessary. Moreover, presented calculations correspond only to one of the numerous fields discovered in the Sakhalin region. The possibility of utilisation of produced carbon dioxide from the other hydrocarbon fields located in the Sakhalin region exists. That, in its turn, increases the economical explanation of the implemented technology.

Along with that, the maximum value of carbon dioxide production will be this year since the full field development started in 2014. This underlines the need for the technology realisation one more time at an early date.

Table 5.3. Calculated annual and cumulative production of gaseous and liquefied carbon dioxide

| Year | Annual $CO_2$ production, billion $m^3$ | Cumulative $CO_2$ production, billion $m^3$ | Annual $CO_2$ production, million tonnes | Cumulative $CO_2$ production, million tonnes |
|---|---|---|---|---|
| 1 | 0.013 | 0.013 | 0.024 | 0.024 |
| 2 | 0.053 | 0.066 | 0.096 | 0.120 |
| 3 | 0.094 | 0.160 | 0.172 | 0.292 |
| 4 | 0.118 | 0.278 | 0.216 | 0.508 |
| 5 | 0.118 | 0.396 | 0.216 | 0.724 |
| 6 | 0.118 | 0.514 | 0.216 | 0.941 |
| 7 | 0.118 | 0.632 | 0.217 | 1.158 |
| 8 | 0.117 | 0.749 | 0.213 | 1.371 |
| 9 | 0.116 | 0.864 | 0.211 | 1.582 |
| 10 | 0.111 | 0.976 | 0.204 | 1.786 |
| 11 | 0.111 | 1.087 | 0.204 | 1.990 |
| 12 | 0.110 | 1.198 | 0.202 | 2.192 |
| 13 | 0.100 | 1.297 | 0.182 | 2.375 |
| 14 | 0.090 | 1.387 | 0.164 | 2.539 |
| 15 | 0.089 | 1.476 | 0.164 | 2.702 |

Table 5.3. Calculated annual and cumulative production of gaseous and liquefied carbon dioxide (continue)

| Year | Annual $CO_2$ production, bln $m^3$ | Cumulative $CO_2$ production, bln $m^3$ | Annual $CO_2$ production, mln ton | Cumulative $CO_2$ production, mln ton |
|---|---|---|---|---|
| 16 | 0.089 | 1.565 | 0.163 | 2.865 |
| 17 | 0.087 | 1.652 | 0.159 | 3.024 |
| 18 | 0.086 | 1.738 | 0.158 | 3.182 |
| 19 | 0.085 | 1.823 | 0.156 | 3.338 |
| 20 | 0.080 | 1.904 | 0.147 | 3.485 |
| 21 | 0.075 | 1.978 | 0.137 | 3.622 |
| 22 | 0.069 | 2.047 | 0.126 | 3.747 |
| 23 | 0.055 | 2.102 | 0.100 | 3.848 |
| 24 | 0.050 | 2.152 | 0.092 | 3.939 |
| 25 | 0.048 | 2.200 | 0.087 | 4.027 |
| 26 | 0.044 | 2.243 | 0.080 | 4.107 |
| 27 | 0.033 | 2.277 | 0.061 | 4.168 |
| 28 | 0.029 | 2.305 | 0.053 | 4.220 |
| 29 | 0.027 | 2.332 | 0.050 | 4.270 |
| 30 | 0.026 | 2.359 | 0.048 | 4.318 |

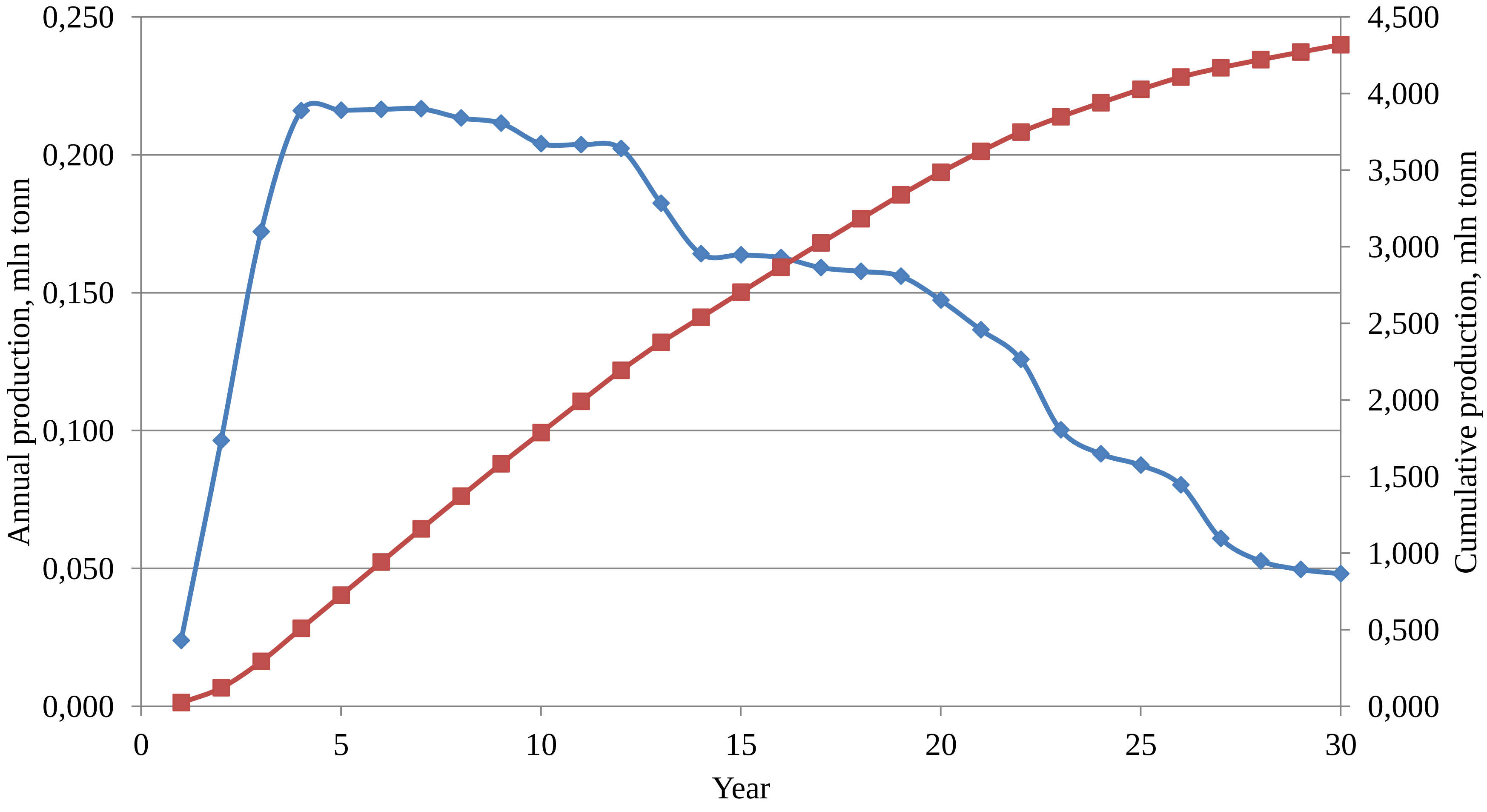

Fig. 5.1. Annual (blue) and Cumulative (red) liquefied carbon dioxide production

## 5.1. Availability of the technological design of the Kirinskoye gas condensate field for the CCS technology implementation

### 5.1.1. Carbon dioxide capture methods applied in the Kirinskoye gas condensate analysis

The main aims and requirements for the capturing of carbon dioxide were described in chapter 3.

In the process of the Kirinskoye field facilities construction, two different methods of capturing of $CO_2$ were analysed. First, the choice of the capturing facility was dictated by the requirements for the dry natural gas. These requirements are presented in Table 5.4. [44]

Table 5.4. The requirements for the dry natural gas

| Parameters | | Values for macroclimatic areas | | Testing method |
|---|---|---|---|---|
| | | Mild | Frigid | |
| Fractional analysis, mole fraction, % | | Makeup is mandatory | - | Russian national standard GOST 31371.1 – GOST 31371.7 |
| Maximum water dew point temperature ($T_{wdp}$) under the absolute pressure is equal to 3.92 MPa, $^{o}C$ | Winter season | -10 | -20 | Russian national standard GOST R 53763-2009 |
| | Summer season | -10 | -14 | |
| Maximum hydrocarbon dew point temperature ($T_{hdp}$) under the absolute pressure is equal to 2.5-7.5 MPa, $^{o}C$ | Winter season | -2 | -10 | Russian national standard GOST R 53763-2009 |
| | Summer season | -2 | -5 | |
| Carbon dioxide mole fraction, % | | 2.5 | | Russian national standard GOST 31371.1 – GOST 31371.7 |

Due to presented requirements for the dry natural gas, two methods of carbon dioxide concentration reduction were analysed: a membrane treatment-processing unit and an amine treatment-processing unit.

The operating principle of the membrane treatment-processing unit is based on the removal of surplus carbon dioxide from the processed gas by use of the three-stage membrane treatment technology.

The principle of operation of the amine treatment unit is based on the removal of surplus carbon dioxide from the inlet fluid flow by use of the amine gas dehydration technology with the help of methyl diethanolamine (MDEA). The same processing unit is used in the Sleipner gas field.

The mass balances of the membrane treatment unit and amine treatment unit are presented in Table 5.5 and 5.6 respectively.

Table 5.5. Membrane treatment processing unit mass balance

| Parameter | | Ratio, kg/h | | Ratio of fluid, % |
|---|---|---|---|---|
| | | In | Out | |
| Raw material | Marketable gas with $CO_2$ concentration is 2.83% | 492455 | - | 98.5 |
| | Stabilized gas with $CO_2$ concentration is 6.70% | 7732 | - | 1.5 |
| TOTAL | | 500187 | - | 100 |
| End product: processed marketable gas with $CO_2$ concentration is 1.90% | | - | 487188 | 97.4 |
| By-product: Permeate with $CO_2$ concentration is 85.00% | | - | 12999 | 2.6 |
| TOTAL | | - | 500187 | 100 |

Table 5.6. Amine treatment processing unit mass balance

| Parameter | | Ratio, kg/h | | Ratio of fluid, % |
|---|---|---|---|---|
| | | In | Out | |
| Raw material: Marketable gas with $CO_2$ concentration is 2.83% | | 503127 | - | 99.8 |
| Energy supply: chemically treated water | | 900 | | 0.2 |
| TOTAL | | 504027 | - | 100 |
| End product: processed marketable gas with $CO_2$ concentration is 1.89% | | - | 492095 | 97.63 |
| By-products | Expansive gas with $CO_2$ concentration is 19.2% | - | 200 | 0.04 |
| | Acid gas with $CO_2$ concentration is 90.9% | | 11732 | 2.33 |
| TOTAL | | - | 504027 | 100 |

For more accurate conclusion, it is necessary to compare the proposed methods of carbon dioxide concentration reduction. There are many parameters of comparison. The two most important parameters are technological and economic accomplishments of the units. The detailed comparison of numbers of characteristics is presented in Table 5.7 below.

Table 5.7. A comparative measure of the membrane treatment unit and amine treatment unit

| Parameter | Membrane treatment unit | Amine treatment unit |
|---|---|---|
| Plant site | The outlet of processed gas after LTS | After the primary separator of LTS |
| Process pressure, MPa | 6.2 | 9.25 |
| $CO_2$ concentration in the processed gas, % | 1.9 | 1.8969 |
| Capacity on amine circulating solution, t/h | - | 108.2 |
| Energy supply and product consumption | | |
| MDEA, t (losses, t/y) | - | 50.0 (25.0) |
| Active carbon, t/y | - | 3.5 |
| Chemically treated water, $m^3/h$ | - | 0.9 |
| Feed water, t/h | - | 5 |
| Fuel gas, $m^3/h$ | - | - |
| Electricity, kW/h | 1190.4 | 910 |
| By-products | | |
| Permeate, $m^3/h$ | 7849 | - |
| Expansive gas, $m^3/h$ | - | 222.3 |
| Acid gas, $m^3/h$ | - | 6763.6 |
| Other parameters | | |
| Footprint, $m^2$ | 34000 | 4500 |
| Site size for industrial purpose, m | - | 50*90 |
| Estimated cost, mln rub (ex VAT) | 3890 | 2000 |

According to the accepted criteria (technological and economic excellence), the amine treatment processing unit possesses a variety of advantages. First, the concentration of carbon dioxide in the natural gas after treatment is lower. Second, the cost of implementation of the amine-processing unit is twice smaller than the cost of the membrane one. Due to the identified advantages of the amine based processing of natural gas, it is recommended to implement exactly this method of capture of carbon dioxide that was realised in the Kirinskoye gas condensate field.

At this stage of the application, analysis of the technology of capture and storage of carbon dioxide in the Kirinskoye field shows that implementation of this technology is possible; however, an analysis that is more accurate should be conducted.

The availability of the capture stage allows continuing the application analysis. Further, the analysis of transportation, injection, and geological storage is presented.

### 5.1.2. Carbon dioxide transportation and injection methods applied in the Kirinskoye gas condensate field analysis

The next and not less important stage of the technology of capture and storage of carbon dioxide is the transportation of the concentrated $CO_2$ stream.

Transportation path of the Kirinskoye field plays a key role on this stage of the CCS technology. Due to field infrastructure development, the transportation path goes both onshore and offshore. The distance from the gas treatment system to the coastline is 16480 m. The length of the pipeline from the bank to the manifold is 28000 m. The total vertical depth where the manifold and wells are located is about 85 m. The slope of the seabed is about $0.2^0$. [43]

According to chapter 3, captured carbon dioxide should be compressed before transportation. Meaning that carbon dioxide should be converted to the supercritical state. Conditions of carbon dioxide supercritical state are presented in Figure 5.2 below.

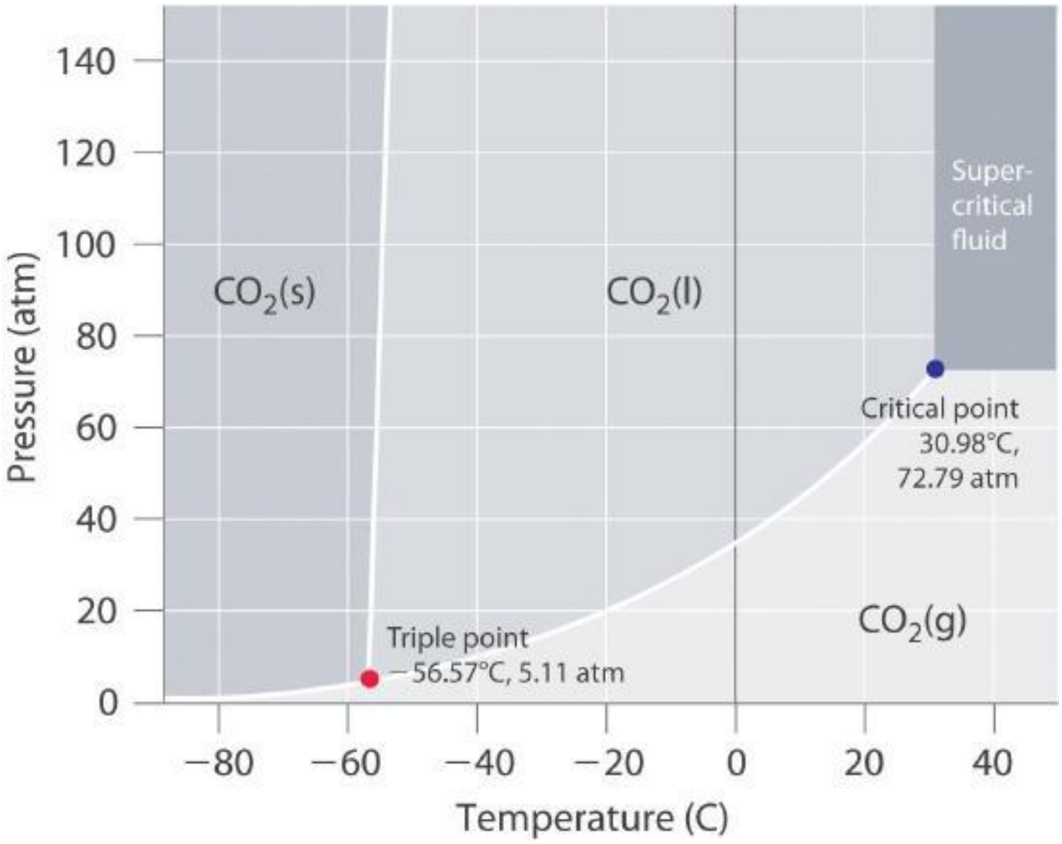

Fig. 5.2. The phase diagram of carbon dioxide [45]

For converting the gaseous carbon dioxide to the supercritical state, compressors are used. To calculate the compression pressure and temperature, and choose the compressors, it is necessary to know these parameters at some point of the pipeline. According to the phase diagram of carbon dioxide and due to the fact that $CO_2$ should be in a critical state through the whole transportation path, the minimum pressure and temperature should be 72.79 atm and 30.98 °C respectively.

It is obvious that minimum pressure and temperature will be on the wellhead. However, to obtain such conditions, a compressor train should be used. It consists of four units, each with a fluid knockout drum to remove water, compressor, cooler and gas turbine driver.

Due to fact that carbon dioxide is just emitted to the atmosphere on the Kirinskoye gas condensate field, it can be concluded that the singular compression train as described above is not used. This means that this stage of the technology of capture and storage of carbon dioxide should be implemented in the near term.

Nevertheless, the most important feature of the transportation stage is to maintain the single-phase flow of concentrated $CO_2$ stream via the injection line. To maintain the single-phase flow it is necessary to keep the supercritical state of carbon dioxide. Further, recommendations for pressure and temperature of the flow are presented. [46]

For calculating the pressure drop, the following assumptions were considered:

- Steady flow;
- No phase transitions;
- Flow rate Q is constant;
- Pure single-phase flow;
- The liquefied carbon dioxide is incompressible z=0, and its density $\rho$ and viscosity $\mu$ are constant;
- Pipeline diameter D and tubing diameter d are constant;
- Roughness $\Delta$ is constant.

Initial data are presented in Table 5.8.

Table 5.8. Initial data for pressure drop calculation

| Parameter | Value |
|---|---|
| Distance from the gas treatment system to the coastline $L_{onshore}$, m | 16840 |
| The length of the pipeline from the bank to the manifold $L_{offshore}$, m | 28000 |
| Slope of the seabed $\beta$, degree | 0.2 |
| Total vertical depth of the sea $TVD_s$, m | 85 |
| Total vertical depth of the well $TVD_w$, m | 2980 |
| Reservoir pressure $P_r$, MPa | 29.5 |
| Reservoir temperature $T_r$, K | 377.15 |
| Flow rate Q, $m^3$/sec | 0.0104 |
| Critical pressure $P_c$, MPa | 7.4 |
| Critical temperature $T_c$, K | 304.15 |
| Critical density $\rho_c$, kg/$m^3$ | 468 |
| Injection pressure $P_{in}$, MPa | 31 |
| Injection temperature $T_{in}$, K | 377.15 |
| Carbon dioxide density $\rho$ under injection pressure and temperature, kg/$m^3$ | 659.5352 |
| Critical carbon dioxide viscosity $\mu$, Pa*sec | 0.00001553 |
| Roughness of the pipes $\Delta$, m | 0.000015 |
| Internal diameter of the onshore pipeline D, m | 0.4636 |
| Tubing diameter of the well d, m | 0.245 |
| Local resistance $\xi$ | 0 |
| Coriolis factor $\alpha$ | 1 |

For successful injection of the concentrated $CO_2$ stream, injection pressure should be larger than the reservoir pressure. For calculations, the injection pressure was assumed 31 MPa.

The following algorithm was used and results were obtained.

1. First, the pressure drop was calculated along the well.

1.1. Flow speed was calculated using the formula:

$$v_i = \frac{4 \cdot Q}{d_i^2 \cdot \pi} \tag{5.2}$$

where index I – number of steps, π – pi number, Q – flow rate, d – tubing diameter.

1.2. Reynolds number Re was calculated as:

$$Re = \frac{V * D * \rho}{\mu} \tag{5.3}$$

where ρ – carbon dioxide density, μ - carbon dioxide viscosity.

1.3. The flow regime was identified using the following classification:

- Laminar flow region:

$$Re < 2300 \tag{5.4}$$

- Hydraulically smooth pipe region:

$$2300 < Re < 10 * \frac{D}{\Delta} \tag{5.5}$$

- Mixed friction region:

$$10 * \frac{D}{\Delta} < Re < 500 * \frac{D}{\Delta} \tag{5.6}$$

- Relatively rough pipes region:

$$Re > 500 * \frac{D}{\Delta} \tag{5.7}$$

1.4. After the flow regime was identified hydraulic resistance coefficient was estimated using the following classification:

- Laminar flow region:

$$\lambda = \frac{64}{Re} \tag{5.8}$$

- Hydraulically smooth pipe region (Blasius formula):

$$\lambda = \frac{0,316}{\sqrt[4]{Re}} \tag{5.9}$$

- Mixed friction region (Altshul's formula):

$$\lambda = 0{,}11 * (\frac{68}{Re} + \frac{\Delta}{D})^{0{,}25} \tag{5.10}$$

- Relatively rough pipes region (Shifrinson formula):

$$\lambda = 0{,}11 * (\frac{\Delta}{D})^{0{,}25} \tag{5.11}$$

1.5. Bernoulli's equation of the steady flow of real incompressible liquid is:

$$z_1 + \frac{p_1}{\rho_1 * g} + \frac{V_1^2}{2 * g}\alpha_1 = z_2 + \frac{p_2}{\rho_2 * g} + \frac{V_2^2}{2 * g}\alpha_2 + \left(\lambda_1 * \frac{l_1}{d_1} + \sum \xi\right) * \frac{V_1^2}{2 * g} \tag{5.12}$$

From the equation (11) following formula for pressure drop was obtained:

$$p_2 = p_1 + \frac{(V_1^2 - V_2^2) * \rho}{2} + (z_1 - z_2) * \rho * g - \left(\lambda_1 * \frac{l_1}{d_1} + \sum \xi\right) * \frac{V_1^2 * \rho}{2} \tag{5.13}$$

Due to assumptions, the flow speed, Reynolds number, the flow regime and hydraulic resistance coefficient are constant and presented in Table 5.9. Pressure drop along the well is presented in Figure 5.3.

Table 5.9. Calculated parameters for pressure drop along the well evaluation

| Parameter | Value |
|---|---|
| Flow speed, m/s | 0.2214 |
| Reynolds number | 2303806.133 |
| 10*d/Δ | 163333 |
| 500*d/Δ | 8166666.667 |
| Flow regime | Mixed friction region |
| Hydraulic resistance coefficient | 0.0107 |

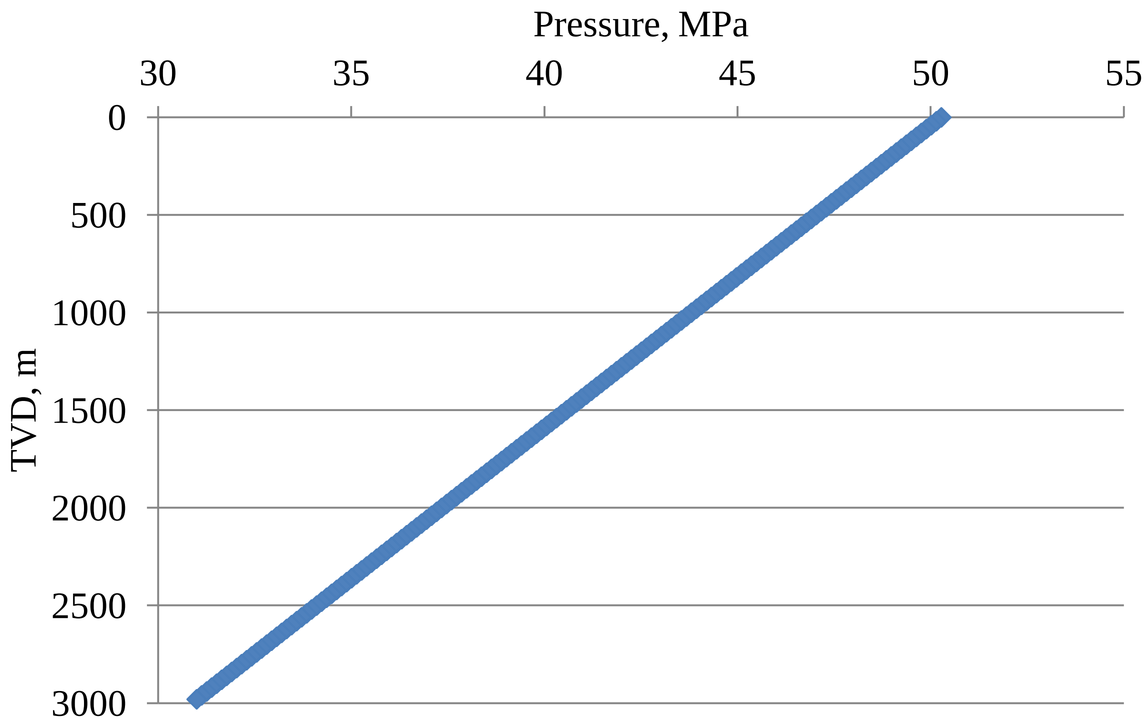

Figure 5.3. Pressure distribution along the injection well

The same algorithm was used to calculate the pressure distribution along the pipeline. The obtained results are presented in Table 5.10. Pressure distribution along the pipeline is presented in Figure 5.4 below.

Table 5.10. Calculated parameters for pressure drop along the pipeline evaluation

| Parameter | Value |
|---|---|
| Flow speed, m/s | 0.0618 |
| Reynolds number | 1217499 |
| 10*d/Δ | 309066.7 |
| 500*d/Δ | 15453333 |
| Flow regime | Mixed friction region |
| Hydraulic resistance coefficient | 0.0107 |

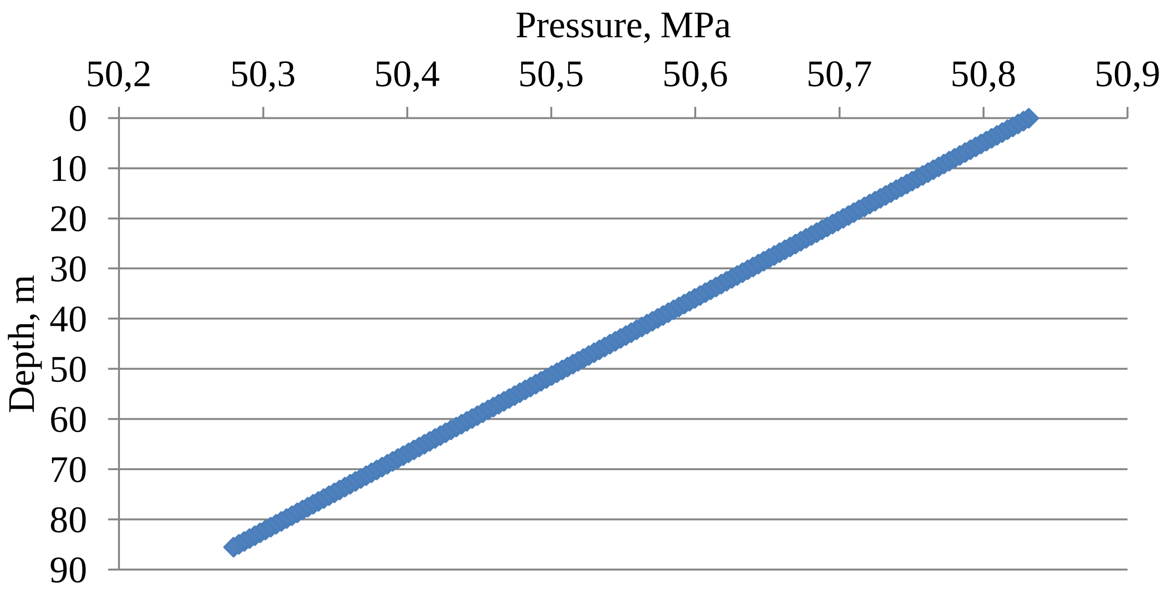

Fig. 5.4. Pressure distribution along the pipeline

The second important characteristic of the keeping the carbon dioxide in a supercritical state is temperature. According to the phase diagram presented in Figure 5.2, to keep carbon dioxide in a supercritical state it is necessary to maintain the temperature of the flow higher than the critical temperature 30.98 °C.

Due to the obtained results, it is concluded that the application of the CCS technology on the Kirinskoye gas condensate field on the transportation stage is limited. First, it is associated to unavailability of injection pipeline and, agreeably, injection well. However, due to the high production rate, it is recommended to transfer one of the producing wells to injection well stock.

Second, the evaluated pressure distribution shows that it would be necessary to compress the carbon dioxide under compression pressure about 51 MPa. Technologically, that process could be conducted, but it is meaningless for this moment. The reservoir pressure is quite high and there is no necessity to maintain it now. However, according to the Table 5.3, reservoir pressure will be twice lower after ten years. The maintaining of the pressure will be needed and the implementation of the technology of capture and storage of carbon dioxide is one of the possible remedies. As for the production of carbon dioxide within this time, it is necessary to build the storage tanks.

## 5.2. Carbon dioxide geological storage in the Kirinskoye gas condensate field analysis

One of the most important conditions for the technology of capture and storage of carbon dioxide realisation is the availability of geologic storage.

As it was mentioned in chapter 3, geological storage of carbon dioxide represents an injection of the concentrated stream of $CO_2$ into a rock formation below the earth's surface. In this case, three types of geological storage could be considered: oil and gas reservoirs, deep saline formations and unprofitable coal beds. It is obvious that listed types have favourable properties to hold and keep carbon dioxide. Aside from, suitable storage formation can occur in both onshore and offshore sedimentary basins. [18]

Besides storing $CO_2$, it can be used for enhancing oil and gas recovery as well as enhance coal bed methane recovery. More information about types and special features of geological storage was described in chapter 3.

According to the Figure 1.10, that presents the prospecting sedimentary basins for storage of carbon dioxide, the Sakhalin region could be considered as a promising storage site. That allows studying the possibility of the CCS technology application more precisely. [12]

It should be noted that for more accurate analysis, reservoir simulation modelling must be done. However, the lack of data does not allow the analysis of the possibility of the concerned technology. Because of this, analysis of the geological storage is conducted by the similarity principle. This principle is widely used during the development of oil and gas fields, but it could not issue the warranty of high quality.

For an analysis of the possibility of geological storage of carbon dioxide on the Kirinskoye gas condensate field properties of the reservoirs were compared to the Utsira hosted formation properties of the Sleipner gas field. The correlation between the parameters is presented in Table 5.11.

Table 5.11. Reservoir properties of the Sleipner field Utsira formation and Kirinskoye field formations

| Formation | Parameter | | | | | |
|---|---|---|---|---|---|---|
| | Stratification depth, m | | Thickness, m | Rock | Porosity, % | Permeability, Darcy |
| | Top | Bottom | | | | |
| Utsira | 800 | 1100 | 50 – 250 | Sandstones | >30 | 1 – 10 |
| Pomyrsky horizon | 119 | 830 | 690 – 730 | Silt, gravel, sands, clays, aleurolite | * | * |
| Nutovo horizon | 830 | 2230 | 1200 – 1500 | Aleurolite, sandstones, clays | * | <0.250 |
| Okobykay horizon | 2230 | 2911 | 400 – 700 | Clays, aleurolite, sandstones | * | * |
| Dagi horizon | 2911 | 2970 | 28 – 200 | Sandstones, aleurolite, clays | 19 – 23 | 0.199 – 0.242 |

From the Table 5.11 above, it is seen, that reservoir properties of the Utsira formation are significantly better than properties of other formations. This emphasises the uniqueness of the Utsira formation one more time and confirms the fact that this reservoir could be considered as a very promising storage according to the Figure 1.10.

However, the obtained results do not show that the application of the technology of capture and storage of carbon dioxide in the Kirinskoye gas condensate field is not possible.

Nutovo horizon of the Kirinskoye field Neocene system could be considered as promising storage of carbon dioxide. It consists of the sandstones as well as Utsira formation. Nevertheless, according to the Table 4.5, the percentage of the sandstones is only 10%. The stratification depth of the Nutovo horizon correlates with the depth of the Utsira formation and presents more thickness. It could mean that the horizon may have more capacity. On the other hand, porosity and permeability of the horizon should be analysed as well for a more accurate conclusion.

Dagi horizon of the Kirinskoye field Neocene system seems to be more favourable for geological storage of carbon dioxide. Despite the differences in stratification depth compared to the Utsira formation, their thicknesses correlate closely. Moreover, the stratification depth of the Dagi formation provides the necessary conditions to keep the concentrated $CO_2$ stream in a supercritical state and reduces the possibility of leakages due to increased gas-tight cap rock thickness. In addition, both formations consist of the sandstones generally. According to the Table 4.5, the percentage of the sandstones of the Dagi formation is about 90%. The porosity and permeability of the concerned horizon are sufficient for geological storage.

However, despite the identified prospective of the Dagi horizon, more accurate analysis with the use of the reservoir modelling should be conducted.

One of the main issues that should be considered during the realisation of the technology of capture and storage of carbon dioxide is monitoring and modelling the distribution of injected $CO_2$.

## 5.3. The legal and regulatory framework of the carbon dioxide emissions and geological storage in Russian Federation. Brief economic analysis

The world community has been worried about the problem of climate stabilisation for a long time. Global warming, acid rains, ozone holes and many others negative consequences of the anthropogenic human activity caused the development of the international legal regime for the prevention of these unfavourable phenomena. [47]

The United Nations Organization (UNO) called to pay attention to the environmental changes. One of the first documents accepted by the UNO for environmental warfare was “The Convention on Long-Range Transboundary Air Pollution”. [47]

This convention obliges the member country to conduct the politics of cooperation in research activity in the prevention of different kinds of pollutant emissions to the atmosphere. The convention was added by several protocols in which Russia does not take part.

The next legislative instrument was “Vienna Convention for the Protection of the Ozone Layer”. This convention called the countries to adopt the consolidated international legal routes for the prevention of pollutant emissions. Harmonisation and integration of the international environmental law are needed to create the unified approach for the anthropogenic factors warfare. In addition to the Vienna convention, “The Montreal Protocol on Substances that Deplete the Ozone Layer” was accepted in 1987. [48]

The listed legal documents were just the first step of the creation of the mechanism of environmental protection.

The accepted modifications to the Montreal protocol could be considered as unique. These modifications involve the reduction, and the total remission, in the future, of five groups of substances production. The creations of the gratuity fund for the developing countries for the environmental safety, implementation of the technologies, etc., were considered as well. [49]

The next step in environmental protection was the acceptance of the United Nations Framework Convention on Climate Change in 1982. This convention was adopted to reduce the greenhouse effect or global warming. [50]

In addition to the Framework Convention, the Kyoto Protocol was adopted in 1997. [51]

According to the Kyoto protocol, the member countries were obliged to reduce the $CO_2$ emissions. The emissions international market was created. Its main aim was the sale of “quotas” for carbon dioxide emissions.

The Kyoto Protocol considers two mechanisms of carbon dioxide emission reduction: “Clean Development Mechanism” and “Joint Implementation Mechanism”.

The essence of the first mechanism is: developed countries could act as sponsors for developing countries in the reduction of $CO_2$ emissions project implementation. This initiative would be counted as a contribution of the developed country to the world reduction of carbon dioxide emissions.

The essence of the second mechanism is: several developed countries implement the project of carbon dioxide emissions reduction jointly.

The Kyoto Protocol considers the reduction of carbon dioxide concentration as well. One of the most useful technologies is the technology of capture and storage of carbon dioxide.

This technology is very important for the Russian Federation. With a high scientific and technical development, such method will allow minimising the $CO_2$ emissions during the oil and gas field exploration. [52]

Russian Federation confirmed the Framework Convention in 1994. However, the confirmation of the Kyoto Protocol was for a long time undecided. [53]

Russia became the full-rate member of the Framework Convention only in 2004. The Federal act “About the confirmation of the Kyoto Protocol to the UNO Framework Convention” was adopted. [54]

After the confirmation of the Kyoto Protocol in Russian Federation, the following actions for its realisation and adaptation were conducted:

- The regulation for the creation of a special list-register of carbon units for substances releases to the atmosphere record was published in 2006; [55]
- A multiagency commission of the Kyoto Protocol realisation was formed; [56]
- The climate doctrine of the Russian Federation was confirmed in 2009; [57]
- The decision “About the realisation actions of the Kyoto Protocol to the UNO Framework Convention” was developed in 2011; [58]
- The decision “About the government regulatory actions of the ozone-harming substances consumptions” was developed in 2014; [59]
- The Russian Federation took part in the Paris agreement to the Framework Convention that regulates the reduction actions of $CO_2$ concentration in the atmosphere. This agreement will replace the Kyoto Protocol in 2020.

In its turn, the conception of the monitoring system forming, reporting and checking requirements for the volume of greenhouse gases releases was confirmed and is realised since 2015. This conception considers three stages of $CO_2$ emissions reduction:

- The first stage is the forming of the rules and regulations, methodological and institutional conditions – 2015-2016 years;
- The second stage is the improvement of the monitoring system, reporting and checking requirements for the volume of greenhouse gases releases – 2017-2018 years;
- The third stage is further improvements of the monitoring system, reporting and checking requirements for the volume of greenhouse gases releases – 2019-2020 years.

All listed actions for carbon dioxide emissions reduction in the Russian Federation are important. However, there is no real method for $CO_2$ emissions reduction in the laws of the Russian Federation.

There are no taxes for carbon dioxide emissions to the atmosphere in Russia. The enterprises voluntarily present the data about the releases amount and are responsible for this.

From this point of view, such conditions bring to nought the procedural frameworks for the $CO_2$ emissions control. The technology of capture and storage of carbon dioxide will be unprofitable without the “ecological taxes”.

*Brief economic analysis*

According to the Constitution of the Russian Federation, pollutant emission to the atmosphere assesses. However, there is no specific tax for carbon dioxide emissions in the Russian Federation.

As it was mentioned in chapter 3, the Norwegian government has imposed a tax to stimulate companies to reduce $CO_2$ emissions. The tax started at a high rate of US$51 per tonne of $CO_2$. Nowadays, the tax reaches the mark of US$65.

Let us assume the tax for the carbon dioxide emissions in the Russian Federation is equal to the Norwegian tax rate. In this case, the redemption through the whole life of the Kirinskoye gas field would be of US$280.67 million. The redemption per year would be US$9.36 million and daily – US$25.63 thousand.

It is obvious, that this tax would be significantly lower if it took place in Russia. However, in any case, the implementation of the technology of capture and storage of carbon dioxide seems to be economically justified. For the precise conclusion, it is necessary to conduct the detailed economic analysis.

## Chapter 6. Risks related to the CCS technology. Risk analysis

This part of the master's thesis describes main risks related to the technology of capture and storage of carbon dioxide.

There are a number of risks associated with usage of the technology of capture and storage of carbon dioxide. These risks are related to both health and safety. This part involves the description of two main technical risks that could occur: hydrate formations and leakages of injected carbon dioxide. It also contents main aspects of possible failure of the system.

The technology of capture and storage of carbon dioxide, first of all, is associated with the capture and concentration of $CO_2$, its transportation, and storage. It should be noted that all of these components have a different level of technological accomplishments. Specifications and development levels of each of the stages were presented in Table 3.1.

According to this data, the technology to capture and storage has not reached the highest level of accomplishments. Therefore, listed stages of the technology are associated with the different risks that should be considered during the implementation of the system.

As for capturing step, it does not present any especial challenges that previously have not been noticed. The most important thing is a significant amount of energy that this component is required for its operation. It means that the net plant efficiency is reduced and power plant requires more fuel to generate electricity. That in its turn leads to additional environmental emissions of other gases and increasing of chemical consumption.

Transportation of carbon dioxide does not represent any fundamentally new challenges as well as its capture. The most important thing is a comprehensive selection of the pipeline materials. Due to the high corrosion activity of the transported fluid, $CO_2$ pipelines have to be made from corrosion-resistant alloys or to be internally clad with an alloy or a continuous polymer coating. [5]

No less important thing is a preventing of leakages that can occur during transportation and storage stages. More information is presented further.

### 6.1. Possible leakages of carbon dioxide

The most important and dangerous risk associated with the technology of capture and storage of carbon dioxide is leakages. That accident can occur during transportation and storage stages.

Leakages during transportation do not represent a high hazard for people and environments because $CO_2$ pipeline's route generally goes through unpopulated territory and presents superficial failure. There are highly effective methods for leakages elimination nowadays and developed monitoring systems that allow controlling the consistency of the pipelines.

Leakages during storage of carbon dioxide are more dangerous and could be considered as global risks and local risks. Global risks represent, for example, climate changes due to significant releases of $CO_2$ from the storage formation to the atmosphere. Local risks are risks that may occur in addition to the global one. These are hazards to humans, ecosystems, and groundwater.

However, as for global risks, modern systems of monitoring of storage sites, high-developed engineering systems, and models provide effective control systems and the retention of the stored carbon dioxide is likely to exceed 99% over 100 years and is likely to exceed 99% over 1000 years or even longer periods of time.

Local risks may occur in two ways. In the first case, the origin of $CO_2$ leakages may be a failure of the injection well or leakage up abandoned wells. This type of leakages could be sudden and rapid, but on the other hand, it could be detected promptly and stopped by use of the available modern techniques of containing well blowouts.

In the second case, leakages may occur through undetected faults, fractures or through leaking wells. Such leakages are more gradual and diffuse. In Figure 6.1 below the potential leakage paths for a saline formation are shown. [5]

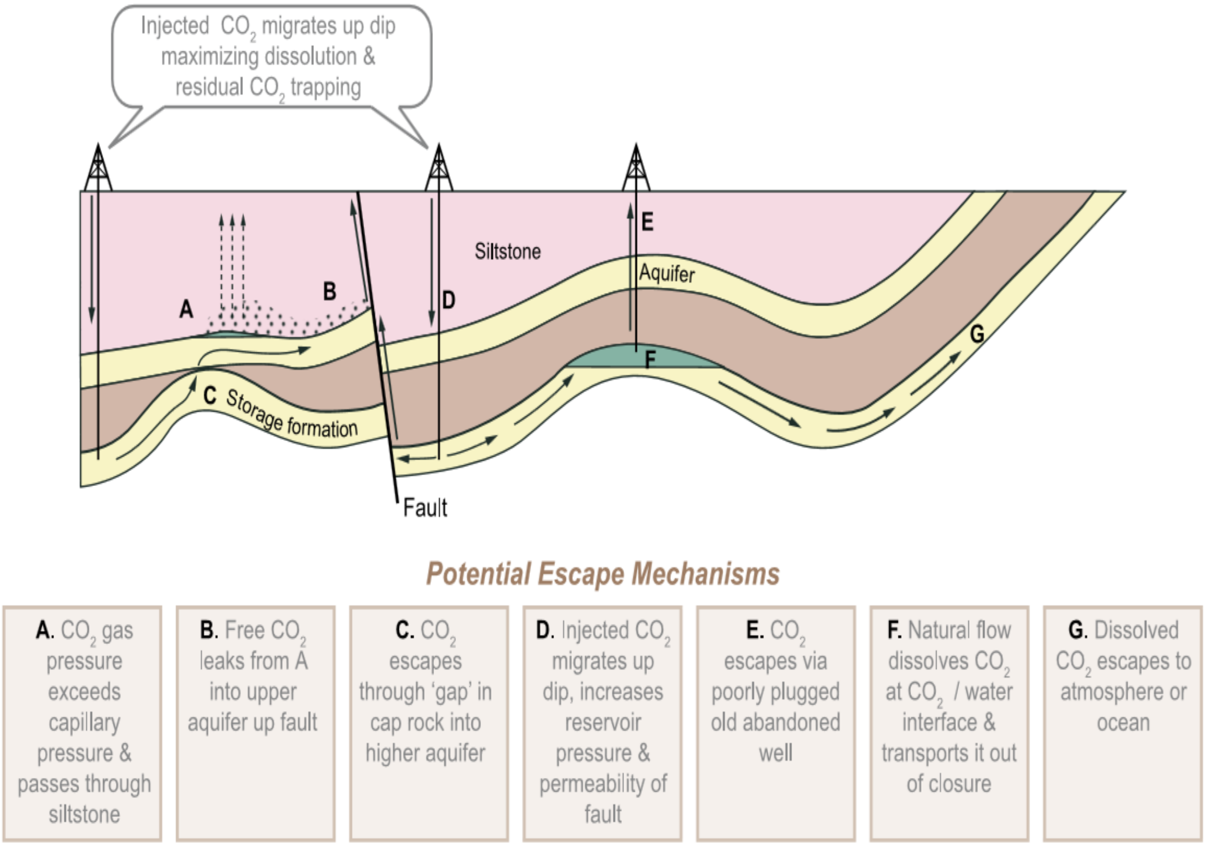

Fig. 6.1. Potential leakage paths for a saline formation [5]

Remedial measures for the illustrated paths of the carbon dioxide leakages are different. A and B cases require to extract and purify ground water. In the case of $CO_2$ escaping through the gap, it is necessary to remove the fluid and inject somewhere else. If $CO_2$ migration occurred and that resulted in increased reservoir pressure (case D), the injection rates and pressure should be lowered. For E case the only way to protect the environment and people and to prevent the replication of the situation is to re-plug well with cement. In two last cases, interception and injection of carbon dioxide are required.

Several accidents have taken place on the Sleipner gas field.

In February 2004, oily water was noticed on the sea surface near the platform of the Ringhorne field. The field started production in 2001. Well cuttings, slop, and fluids were injected into the Utsira Formation. The leakages were observed to be coming from the injection well.

In 2007, unexplained activities on the seabed were noticed near the Visund field. Gas, well cuttings, slop, and fluids were injected into the Utsira Formation as well. Observed activities probably were related to the injections. Most likely, it was a form of cracking or other damage to the formation.

In May 2008, workers on the Gulfaks platform in the North Sea happened to notice oily water near their platform. The produced water from the Tordis field had been injected into the Utsira Formation. The investigations conducted that it had resulted in cracking of the seabed above the reservoir. Thereby, a stream of the produced water had allowed it to escape back to the sea. [60]

The information above suggests that the Utsira Formation is not an ideal reservoir for different injections as it was considered. The probability of leakages exists. Obviously, the monitoring and modelling conducted by operating companies were wrong.

Such practice notes that the probability of carbon dioxide leakages exists as well. The main reason is that injected stream cannot stay in a liquid form due to a too shallow depth of the formation to provide the pressure required to the safe supercritical state of carbon dioxide. $CO_2$ starts to vaporise that result in easier and faster leakages.

In this case, more accurate analysis, monitoring, and modelling of the movements of the injected carbon dioxide should be conducted. Such technologies require more detailed characterization of the field and more proper management in order to prevent possible leakages and corresponding consequences.

### 6.2. Failure of the CCS technology

Another and very important issue is: “What to do if implemented the technology of capture and storage of carbon dioxide stopped working?”

That question is a really great part of the realisation of CCS technology. Special attention should be paid to this failure during the design stage of the technology. Engineers have to make an accurate decision regarding this issue.

It is necessary to keep in mind that failure of the system may occur at any step of the technology: the capture of carbon dioxide, its transportation, and storage. During capture stage one of the system components, for example – separator, may be out of order. Transportation stage involves hundreds of pipelines that should be checked carefully to avoid failure of the system. During the design stage of the technology, engineers have to analyse carefully each step of the system and create additional lines of approach in the case of the problem described.

There are two ways that lead to such failure: an inability to inject carbon dioxide due to system breakdown, and an impossibility to inject $CO_2$ due to host formation cracking, properties changing, etc.

As for the second reason, there are no ways of avoiding that failure from the global point of view. The only way is to change formation to another with all coming consequences: more accurate surveys of selected reservoir, drilling of a new injection well, trial injection of carbon dioxide and monitoring of its distribution and movements, etc. It is obvious that it will result in huge capital investments. Such a chain of possible events confirms one more time the necessity of accurate analysis of the properties and host capacity of the selected formation and detailed design of the technology of capture and storage of carbon dioxide.

The possible decisions are more simple and available from the local point of view. Such failure of formation as cracking of the cap rock, for example, could be easily eliminated by placing the cement plug or by applying other technologies that are widely used nowadays.

As for the Utsira Formation, that failure is not possible according to the obtained results of the surveys from a global point of view. It is estimated that this formation is capable of storing 600 billion tonnes of carbon dioxide. Properties of cap rock and host reservoir are quite good. That is why the Utsira Formation is considered as unique.

Possible solutions in case of the system breakdown could be:

- Spare injection well;
- Readiness to remove and replace problematic module;
- To conduct support work of the system;
- To replace the problematic equipment before the failure;
- Etc.

Anyway, companies have to be ready to this failure, even if the survey's results and proper design of the technology were completed.

## 6.3. Potential hydrate formation

Numbers of gases are able to format hydrates.

Gas hydrate – is crystalline water–based solid, in which gas molecules are trapped inside “cages” of frozen water molecules. Special conditions are required to format the gas hydrate. It means that certain pressure and temperature are needed. These conditions are different for different gases due to its contrasting molecule structures, boiling point temperatures, saturation pressures, and other characteristics.

It is easier and cheaper to prevent hydrate formation than segregate already formed and accumulated hydrates. Methods of segregation are classified as:

1. Decreasing the pressure below the pressure of decomposition;
2. Heating of the gases above temperature of the decomposition;
3. Inhibitors injection.

Methods of avoiding of hydrate formation are classified as:

1. Inhibitors injection;
2. Gas drying;
3. Maintenance of the temperature of the gases above temperature of hydrate formation;
4. Maintenance of the pipeline pressure below the pressure of hydrate formation. [61]

$CO_2$ is a hydrate formation gas as well. [62]

Conditions under which carbon dioxide can become a hydrate are presented in Figure 5.2. [45]

As it was mentioned, captured carbon dioxide is in its supercritical state after the compression. According to phase diagram, hydrate formation is not possible in such conditions. Hydrate formation inside of Utsira Formation is not possible either. Estimated pressure and temperature at the top of the reservoir are 8.6 MPa and 29 °C respectively.

However, during the injection of carbon dioxide, there is a possibility of hydrate formation in a cross-section of the well due to temperature differences inside and outside the pipe. There are several mechanisms contributing to hydrate formation. They are the following:

- The free and dissolved water in the flow;
- Low temperatures;
- High pressures.

The purity of injected $CO_2$ is about 98 percent. The remaining 2 percent is methane. Therefore, water presence in the flow is not possible or overly small after removing with separators, glycol dehydrators, molecular sieves or other methods that could be implemented.

Temperature and pressure maintaining are issues to which attention should be paid. The temperature is low and the pressure is significantly higher during the injection. These conditions increase the possibility of hydrate formation.

Different methods exist to prevent hydrate formation. The most applicable method to avoid hydrate formation is an inhibitor injection. These are classified as:

- Environmental inhibitors;
- Thermodynamic inhibitors;
- Kinetic inhibitors.

Thermodynamic inhibition has been the most common method to prevent hydrate formation. The thermodynamic inhibitors could be a monoethylene glycol, diethylene glycol, triethylene glycol, etc.

As for Sleipner gas field, hydrate formation is not an issue. The carbon dioxide stream is sufficiently dry to provide prevention of hydrate formation. The way to obtain an optimal operational window is to keep $CO_2$ too dry. Due to carbon dioxide properties, this is possible and does not require any special investigations.

So far, no incidents have occurred regarding hydrate failures in the injection well. This, mainly due to careful engineering. However, the field is at a reasonably high risk in terms of humidity content and temperature. [63]

The issue related to hydrate formation should be taken into account at the stage of concept field development design. Further, the simplified methodology is presented. It could be useful for any offshore oil and gas fields that use the technology of capture and storage.

The methodology is based on Bernoulli's equation (6.1).

$$\left(L+\frac{P_{top}}{\rho g}+\alpha_0\frac{V_0^2}{2}\right)-\left(\frac{P_{bottom}}{\rho g}+\alpha_1\frac{V_1^2}{2}\right)=H_{up-bottom} \qquad (6.1)$$

Where L – Occurrence depth of the formation below the sea bottom, m;

$\alpha_0$, $\alpha_1$ - Coriolis coefficients (often equal 1);

$V_0$, $V_1$ – Velocities of gas stream in different cross – sections of the pipe, m/s;

ρ – Density of injected gas, kg/m$^3$;

$H_{top\text{-}bottom}$ – losses due to friction, m.

Taken into account that the stream is injected via the same well, equation (6.1) becomes:

$$\left(L+\frac{P_{top}}{\rho g}\right)-\left(\frac{P_{bottom}}{\rho g}\right)=H_{up-bottom} \qquad (6.2)$$

Losses occur due to losses along the pipe length and local resistances such as valves, pipe bends, etc. Assume that local resistances are absent. In this case, losses could be found via equation (6.3):

$$H_{up-bottom}=\frac{8L\lambda Q^2}{d^5\pi^2 g} \qquad (6.3)$$

Where Q – Gas flow pressure, m$^3$/sec;

d – Pipe diameter, m;

g – Gravitational constant, m/sec$^2$;

λ – Hydraulic resistance coefficient.

In this case equation (6.2) becomes:

$$\left(L+\frac{P_{top}}{\rho g}\right)-\left(\frac{P_{bottom}}{\rho g}\right)=\frac{8L\lambda Q^2}{d^5\pi^2 g} \qquad (6.4)$$

The only unknown parameter in the equation (6.4) is pipe diameter. So, it could be found in the following way:

$$d = \sqrt[5]{\frac{8L\lambda Q^2}{(\frac{P_{bottom} - P_{top}}{\rho g} - L)\pi^2 g}} \tag{6.5}$$

Therefore, using the parameters of injection we can find the diameter of the well that would contribute to the prevention of hydrate formation. This in its turn will provide us more thorough geometry of the well. Certainly, this simplified methodology should be added by more accurate estimation.

### 6.4. Risk analysis

It is well known that any activity related to the oil and gas industry is associated with multiple systems of different structure risks. Effective consideration of these risks and development of mechanisms for reducing of possible impairment due to unfavourable situation's effect on the financial performance of the project.

In spite of general understanding of the necessity for risk consideration and significant success in developing of mathematical background of risks theory, the universal methodology of formalisation risk analysis and risk management still does not exist. [64]

Risks theory consists of several risk classifications. The risks are generally classified according to the following characteristic:

- Physical origin (e.g., information and other);
- Stage of the problem solution (e.g., exploration stage and other);
- Risk area (e.g., geological modelling and other);
- Insurance ability;
- Business types;
- Diversification ability;
- Admissibility.

Risks can be classified as well as systematic (general) and non-systematic (local) risks. The first one includes geological risks, external risks, internal risks and others. The second one banks the systems of specific risks such as undiscovered fields, sub-economic production, imperfect and ill-defined information, project risk realisation, market conditions, force-majeure circumstances and others.

Therefore, there are two types of risk systems from a financial point of view:

- The first one is connected to the area of project realisation;
- The second one is associated with technological processes of fields' development such as oil and gas prospecting risks, geological risks, technological risks, economical risks and ecological risks.

During the process of field development changes in the structure of the risk systems take part due to risks composition and its relationship to accumulation risk – risks phylogeny.

Special strategies are used for effective assessment of risk systems changes: risks modelling algorithm and algorithm of long-term overidentification of modelling. [65]

Risk analysis is used for probability evaluation of financial project realisation. A major part of risk analysis methods are based on mathematical statistics that include following statistical criteria: probability, the range of deviation, mean value, variance, least square mean value, the coefficient of variation. [66]

Risk analysis can be executed using different methods. These methods are:

- Risk area classification;
- Ranking or expert appraisal of risk rating;
- Sensitivity analysis;
- Scenario method;
- Event tree analysis; [67]
- Simulation modelling; [68]
- Discount rate review technique.

Risk area classification based on HAZID identification is presented in this master's thesis. [69]

Proper risk analysis should be made in order to estimate possible failures and its consequences. Every offshore project can have the following risk categories:

- Risk to personnel;
- Risk to environment;
- Risk to reputation;
- Financial risk.

Risks analysis algorithm includes the following steps:

1. Upload accept criteria.
2. Hazid identification.
3. Risk evaluation: probability and consequences.

4. Risk mitigation measures

Risks were analysed according to this algorithm.

1. Accept criteria are:

- Health and safety;
- Environment;
- Asset;
- Reputation.

2. Hazid identification.

During this step, it is necessary to determine what can go wrong?

As it was mentioned, there are a number of risks associated with the technology of capture and storage of carbon dioxide. They can be classified as:

- The known hazards;
- The known unknown hazards;
- The unknown unknown hazards.

This project covered three technical risks: hydrate formation, leakages, and system breakdown. All of them can be determined as the known hazards because they are widely famous and different technologies could be applied to prevent them.

3. Risk evaluation: probability and consequences.

For evaluating the level of the risks, the risk matrix is used. It is necessary to evaluate the level of risks for all accepted criteria for all possible failures. Risk evaluations are presented further.

Table 6.1. Event probability

| Accept criteria | Low probability | Medium probability | High probability |
|---|---|---|---|
| Health and safety | < 2% | 2% < P < 10% | > 10% |
| Environment | <5% | 5% < P < 15% | > 15% |
| Asset | < 2% | 2% < P < 10% | > 10% |
| Reputation | < 1% | 1% < P < 5% | > 5% |

The same range should be made for consequences of different events. The obtained results are presented in Table 6.2. This project covers three technical failures that could occur. Thereby, risk analysis is conducted for these failures. Detailed descriptions of the three of them have been presented above. Explanation referring to a particular type of event is presented further.

Table 6.2. Event consequences

| Accept criteria | Low | Medium | High |
|---|---|---|---|
| Health and safety | None hurt | Less than three people are injured | More than three people are injured |
| Environment | Without consequences | Small pollution that could be easily eliminated | Serious consequences caused migration of animal, fishes, etc. or species extinction |
| Asset | Damaged equipment is still useful | Small repair of equipment | Complete replacement of equipment |
| Reputation | Not affected on reputation | The appearance of the smallest confidence in the company | A complete loss of confidence in the company |

*Leakages*

Several accidents have taken place on the Sleipner gas field. Meaning that probability of leakages exists. It is obvious that leakages of carbon dioxide are the most dangerous and unpredictable failure that can occur. The consequences could be different. It depends on point of consideration of the leakages. They can be classified as local and global. Local leakages relate to workers who are involved in the process of injection, to the surrounding environment, and to subterranean water. At the same time, global leakages are associated with people living near the field and for ambient generally. The first one is a more important issue for engineers. The second type is important as well, but generally, ecologists are more appropriate to draw a conclusion in this case.

Thereby, local leakages, its probability, and consequences are analysed further.

- Health and safety

Carbon dioxide is not as dangerous for people as it dissolves into the air. But, a high concentration of carbon dioxide can cause asphyxia, anoxemia, insensibility and death as well. Therefore, the leakages are a very important issue from the health and safety point of view.

- Environment

The consequences of leakages for the environment are the most important issue that has to be taken into consideration. Such failure can cause heavy consequences and harm ambient easily.

- Asset

The leakages of carbon dioxide coming from the reservoir are not so dangerous for equipment. It may cause a number of small consequences, such as corrosion for example.

- Reputation

The leakages are the worst failures that can occur from a reputation point of view. If any happened, the operating company loses confidence immediately. Therefore, leakages are not acceptable from a reputation point of view.

*Failure of the technology of capture and storage of carbon dioxide*

- Health and safety

Failure of the system for health and safety of personnel could cause serious consequences. Firstly, it will result in leakages of carbon dioxide. In this case, it could be considered as a precious issue.

- Environment

Pollution of the environment in case of technology breakdown could be considered from the global and local point of view. Anyway, such failure will affect the ambient dramatically.

- Asset

Failure of the technology of capture and storage of carbon dioxide, as it was mentioned, could be caused by equipment breaking. It means that the consequences of such event will be serious.

- Reputation

It is well known, that the reputation of the company is the most important thing for the management. So, any accidents related to the technology breakdown will affect the reputation seriously.

*Hydrate formation*

- Health and safety

As it was mentioned, no indications have been reached regarding any hydrate failure in the injection well on the Sleipner gas field. It means that the probability of hydrate formation according to statistical data is very low. The consequences of hydrate formation are not so dangerous to the health and safety of the personnel and could be easily eliminated.

- Environment

The probability of hydrate formation is low. The consequences of this event could be different. But, according to statistic data, such failure does not cause heavy consequences and hydrate formation could easily be eliminated.

- Asset

As for asset, risk evaluation is stricter. Firstly, it is associated with the very high cost of equipment and secondly with expensive work to repair and replacement. But mainly hydrate formation does not result in serious consequences for equipment.

- Reputation

Despite the hydrate formation is an easily eliminated event, the reputation of the operating company is the most important thing for the management. That is why the company has to avoid hydrate formation.

Risk matrixes could be constructed after a brief analysis of possible events. Abbreviations HF, L, and SB mean hydrate formation, leakages, and system breakdown respectively.

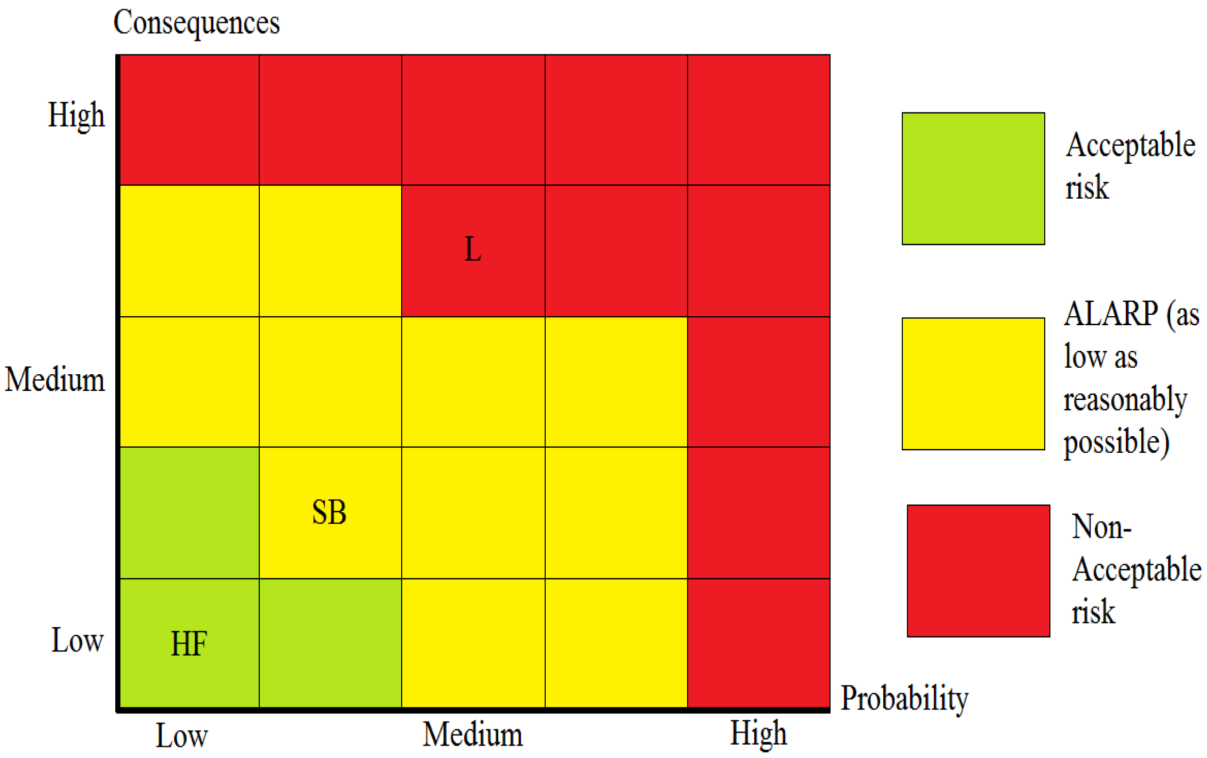

Fig. 6.3. Risk matrix for health and safety of personnel

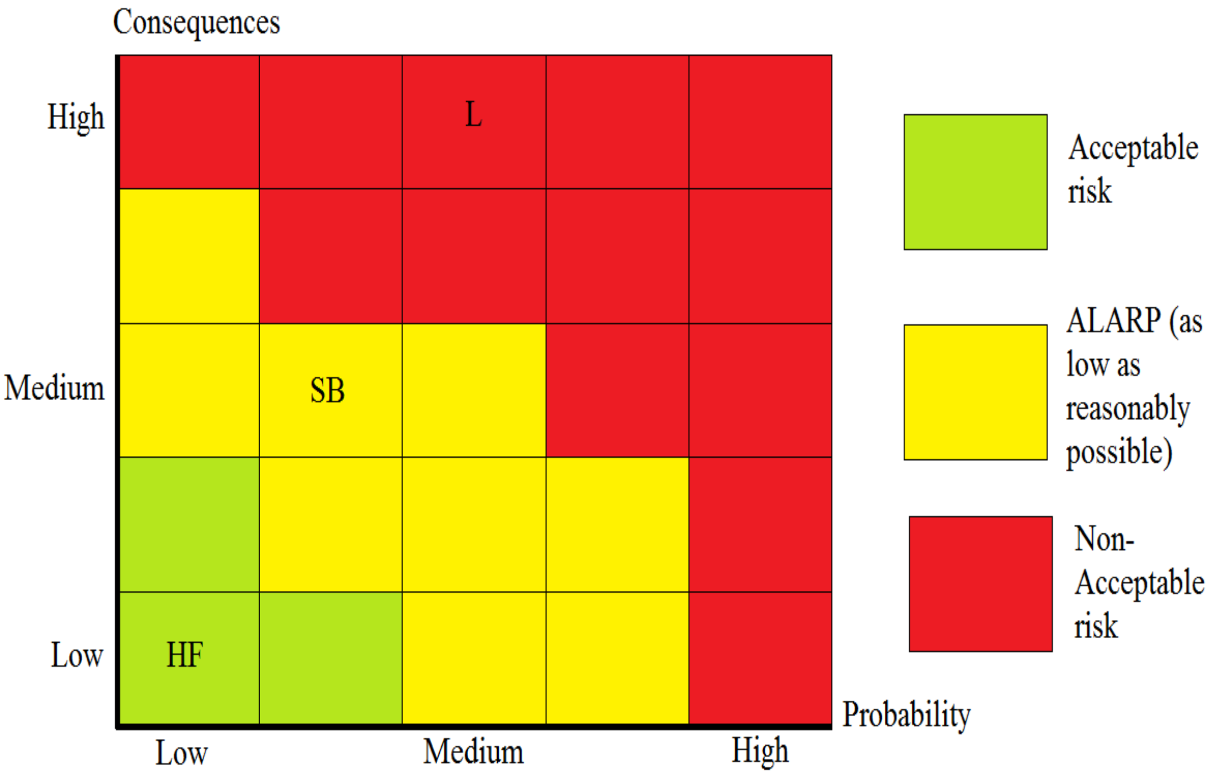

Fig 6.4. Risk matrix for environment

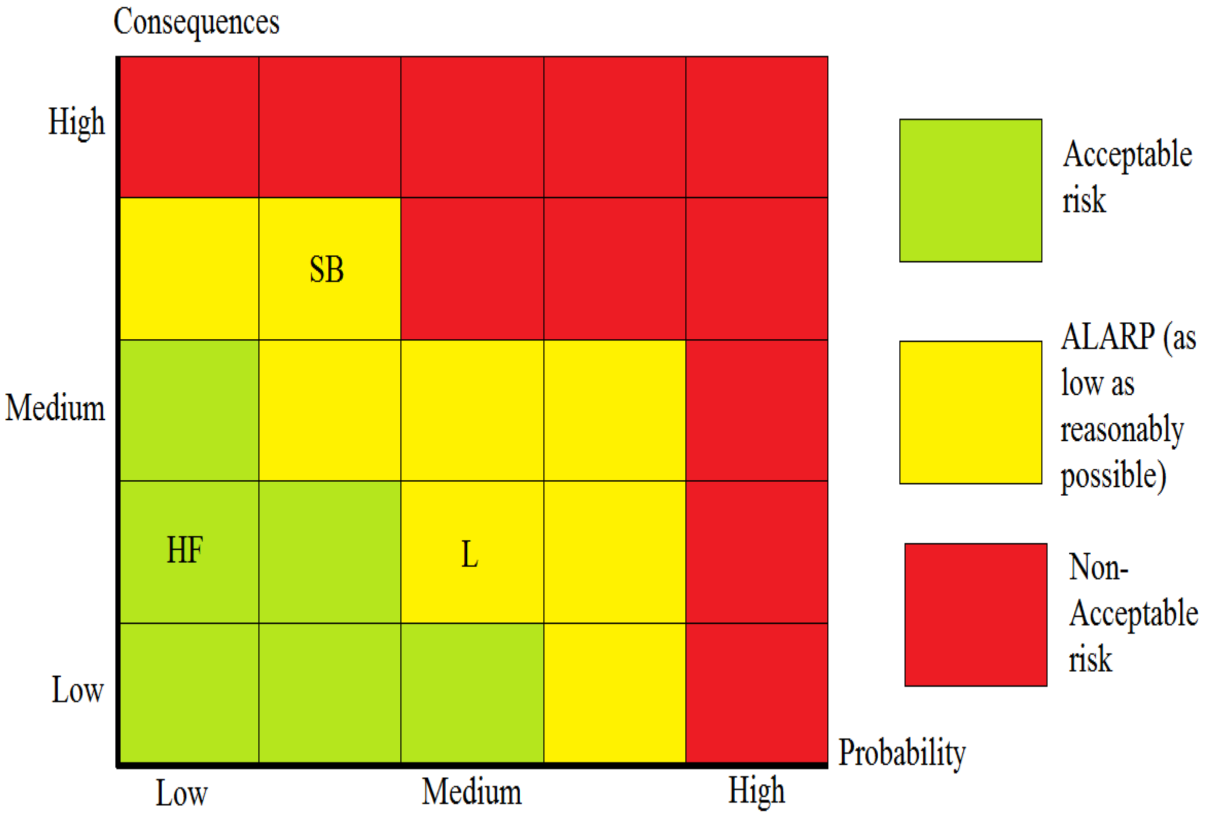

Fig. 6.5. Risk matrix for asset

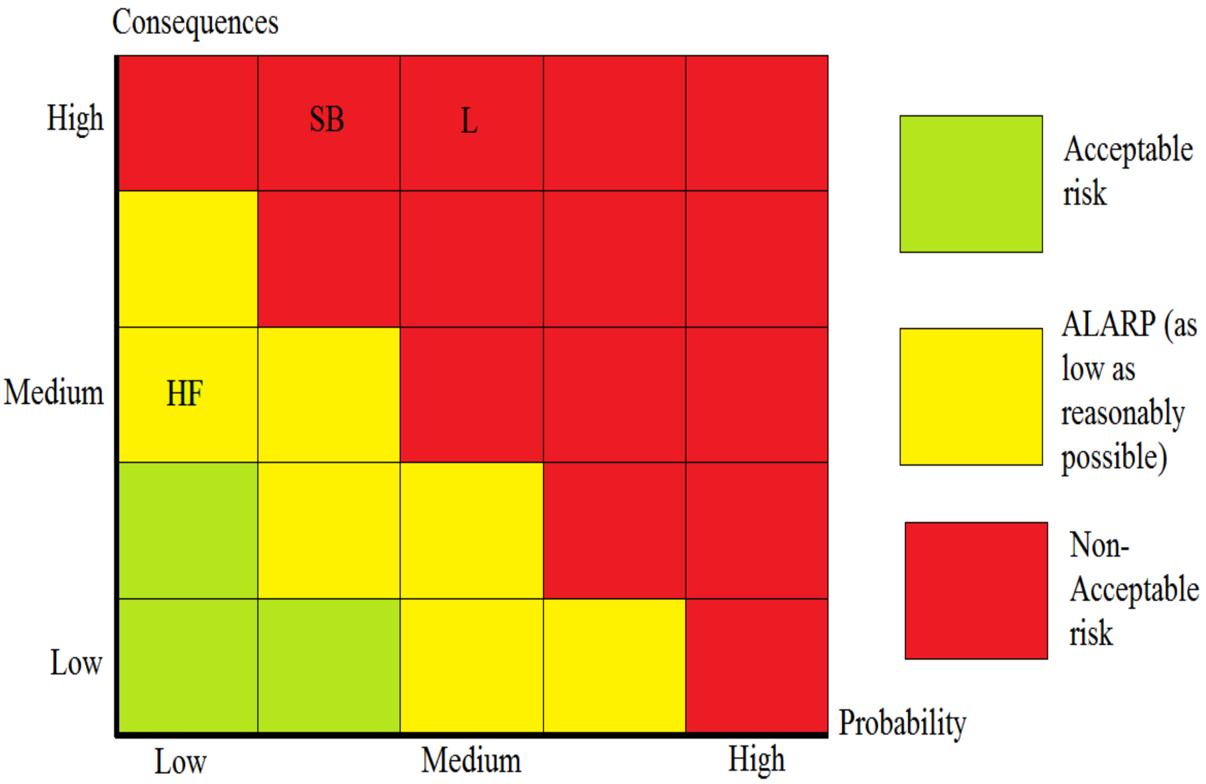

Fig. 6.6. Risk matrix for reputation

4. Risk mitigation measures

Mitigation measures are needed to prevent an appearance of considered failures. A number of tools and technologies are applied to reduce the probability of described events and possible consequences. However, no technology could guarantee 100% of success.

Firstly, proper design and technology project should comply. The probability of appearance of different kinds of failures generally depends on decisions of the risk assessment team. Nevertheless, it is well known that project is often different from reality. It may be associated with lack of data or inadequate skills of the engineers during the project design stage.

Secondly, different technologies and methods should be constantly available in case of failure occurrence. A number of techniques and tools are developed to prevent events considered in this project.

Hydrate formation could be prevented by using one of the following methods:

- The free and dissolved water removal by any kind of absorption or adsorption;
- Maintaining the high temperature of the stream;
- Maintaining low pressure during injection;
- Inhibitors injection.

$CO_2$ leakages require more sophisticated tools and surveys. In spite of numbers of conducted surveys, leakages coming from the Utsira Formation have taken place. Thus, one more time approves the complexity of CCS technology realisation. An extensive program in the Utsira Formation has been undertaken by a number of organisations. The followings surveys are included in this program:

- Baseline 3D seismic survey;
- Eight times lapse 4D seismic surveys;
- Four seabed microgravimetric surveys;
- One electromagnetic survey;
- Two seabed imagining survey. [13]

# Conclusions

Master's thesis is devoted to the technology of capture and storage of carbon dioxide and issues regarding that technology. Such aspects as $CO_2$ sources, $CO_2$ emissions and their consequences, technical excellence of all stages of the technology and their specific features, application analysis of the technology on the Russian continental shelf, in particular in the Kirinskoye gas condensate field, as well as risk analysis of CCS technology implementation were analysed. The following results were obtained.

There are a number of sources of $CO_2$ emissions:

1. Natural sources are ocean-atmosphere exchange, plant and animal respiration, soil respiration and decomposition, and volcanic eruption;
2. Anthropogenic sources are burning fossil fuels, deforestation, industrial processes and others.

Consequences of $CO_2$ emissions are different:

1. Global consequences such as sea level rising;
2. Local consequences such as temperature changing on places;
3. Consequences of industrial emissions such as drug action on people.

According to the results of the analysis of the technology, it has not reached a high level of accomplishments. Therefore, further development and investigations are necessary, especially to its main components – capture and storage.

The main purpose of the thesis was the application analysis of the CCS technology on the Russian continental shelf. Application analysis was conducted in the context of the Kirinskoye gas condensate field.

Two key features were analysed: availability of the technological design of the Kirinskoye gas condensate field and characteristics of the hosted formation. The following results were obtained:

1. Capture stage of carbon dioxide is applicable;
2. Transportation and injection stages of captured carbon dioxide are limited;
3. Geological storage stage of carbon dioxide is applicable.

As well as other technologies associated with possible risks, the technology of capture and storage is not an exception to be associated with risks. There are many different risks related to CCS technology. The most important risks are hydrate formation, leakages, and system breakdown. All mentioned failures were considered and risk analysis was completed.

The technology of capture and storage of carbon dioxide should be developed more accurately and used more widely, as the technology is considered as one of the most effective variants for reducing carbon dioxide emissions to the atmosphere because of human activity. In this case, the implementation of the technology of capture and storage of carbon dioxide seems to be helpful from the contribution of the Russian Federation to the climate stabilisation point of view.

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