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Reduction potentials and abatement costs for methane emissions associated with compromised wellbore sealing systems in Russian oil wells

A Master's Thesis submitted for the degree of
“Master of Science”

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Affidavit

I, **SVETLANA KIRILIUK BSC MSC**, hereby declare

1. that I am the sole author of the present Master's Thesis, "REDUCTION POTENTIALS AND ABATEMENT COSTS FOR METHANE EMISSIONS ASSOCIATED WITH COMPROMISED WELLBORE SEALING SYSTEMS IN RUSSIAN OIL WELLS", 95 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted the topic of this Master's Thesis or parts of it in any form for assessment as an examination paper, either in Austria or abroad.

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Abstract:

The growth of methane concentration in the atmosphere affects climate change (United States Environmental Protection Agency (EPA), 2021). Methane has a global warming potential over 100 years that is 25 times higher than Carbon dioxide (CO2) per ton gas released (Forster & Ramaswamy, 2007). About 60% of global methane emissions are coming from human activities, including oil and gas, which contributes 33% (United Nations Economic Commission for Europe (UNECE), 2021). Methane emissions are possible across the whole supply chain of the oil and gas industry, from oil exploration to the end-user. This study focuses on the emission group in the oil upstream segment, associated with the well's failed sealing system. The first objective of this report is to assess the possible reduction of methane emissions associated with failures of the well's sealing system in those cases where repair is technically feasible. The second objective is to evaluate the required costs for implementing such measures in the context of additional expenses for each produced ton of oil.

Several chapters of the study introduce the reader to the term well integrity, explaining the basic principles of the well construction process and the possible causes of integrity failures. Emissions reduction estimation requires several parameters, and some are not available (e.g., not measured), such as the share of the oil wells in Russia with integrity issues. Therefore, experts with vast experience in Russia's oil and gas industry were surveyed to fill the informational gaps and determine the required parameters.

The study discovers that it is possible to reduce methane emissions associated with the well's integrity issues by 78 kt CH4 a year, representing 17% of the category "Oil and venting" from the oil upstream segment in Russia (462 kt CH4 per year as of 2017). Additional costs would be required to restore the integrity of wells in Russia to mitigate methane emissions estimates as 3 US$ per ton of oil produced. Well integrity restoration has a double positive implication. The positive effect on climate change by methane emissions reduction. Additionally, the oil producers would also benefit from the integrity restoration due to the extended life of the well, and increased of oil production. Therefore, targeting oil wells' integrity to reduce methane emissions could be quick to implement and relatively low-cost solution for methane emissions reduction in the oil upstream segment.

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Abbreviations:

AER	The Alberta Energy Regulator
AI	Artificial intelligence
APB	Annular Pressure Build-up
APG	Associated petroleum gas
API	American petroleum Institute
BC OGC	Columbia Oil and Gas Commission
BU	Bottom Up approach
CBLs	Cement bond logs
DHSV	Downhole Safety Valves
ECCC	Environment and Climate Change Canada
EIA	International Energy Agency
EPA	U.S. Environmental Protection Agency
GHG	Green House Gases
GM	Gas migration
GOR	Gas/oil ratio
HPT	High-precision temperature
ID	Internal diameter
IMEO	International Methane Emissions Observatory
ISO	International Organization for Standardization
LDAR	Leak detection and repair
NEA	Norwegian Environment Agency
NIR	National Inventory Report
NOC	National oil company
OJSC	An open joint-stock company
P&A	Plugging and abandonment
SCP	Sustained casing pressure
SCVF	Surface casing vent flow
SCVT	Surface casing vent test
SDS	Sustainable Development Scenario
SINTEF	Norwegian: Stiftelsen for industriell og teknisk forskning
SMEs	Small and medium-sized enterprises
SNL	Spectral noise logging
TD	Top Down approach
UNFCCC	United Nations Framework Convention on Climate Change
VRU	Vapor Recovery Unit
WOR	Water/oil rati
ECE	The United Nations Economic Commission for Europ

Chapter 1. Introduction

In the last few decades, alternative energy sources, such as photovoltaics, had excelled in technical performance and economic efficiency. According to the World Energy Outlook's Sustainable Development Scenario (SDS), which is consistent with the Paris Agreement's climate goals, oil demand would have to decline by three mb/day between 2019-2025 (IEA (International Energy Agency), 2021). Global oil demand in 2019 was 100.1 mb/day (Statista, 2021). Energy transition towards renewable sources is urgently required to achieve climate goals. Whatever the transition pathway may be, the oil and gas industry has an important role in minimizing emissions, particularly greenhouse gases (GHG's) from industry operations, which is a pressing priority.

Oil and gas production has an important role in a country's economic development and per capita income; for example, in the United States of America (US), oil and gas production secures more than ten mln jobs (Oil and gas journal, 2021). Russian Federation (referred to as Russia) also depends on the oil and gas industry, with 39% of the country's GDP coming from oil and gas-related activities (Ministry of Finance of the Russian Federation, 2021). Pollution, particularly GHG emissions, is a central issue of the industry.

Crude oil and natural gas are the mixtures of hydrocarbons-chemical molecules that contain only hydrogen and carbon. Crude oil is liquid both underground and at surface conditions. Natural gas at normal surface conditions is a vapor, and underground it can exist as a vapor or be dissolved in crude oil. The simplest hydrocarbon molecule is methane, and it is the essential ingredient of natural gas (U.S. Energy Information Administration, n.d.). Methane is also a powerful GHG that contributes to climate change. Methane is more than 25 times as potent as carbon dioxide (CO2) per ton at trapping heat in the atmosphere (United States Environmental Protection Agency (EPA), 2021).

Downhole leaks in oil and gas wells are a public concern primarily due to the possible risks of aquifer contamination and GHG emissions. The issue of unwanted reservoir fluids (gas, oil, and water) seepage into the wellbore is not new. Already in 1987 gas, oil and water showing during well construction and prevention measures were laid down in the "Regulations of oil and gas fields" (Soviet Union Industrial Standard, 1987). However, at that time, the major concern of unwanted gas inflow was health and safety risks.

It is a complex geopolitical and technical issue to tackle methane emissions in oil and gas industry, and various initiatives have been launched. Besides the climate change threat, caused by the higher heating value of methane than CO2, methane emissions are financial losses and safety risks (as methane is highly explosive), thereby securing oil and gas producers' interest to control emissions.

The role of methane emissions caused by wellbore leakages has not been widely studied or reported. The unwanted flow of wellbore fluid occurs when the wells' initial sealing structure or so-called well integrity is compromised. A reliable and enduring well sealing structure during its lifetime and beyond would be beneficial for the oil and gas producing companies due to the extended life of the well and the goodwill received due to prevented methane emissions. The goal of this thesis is to assess methane emissions caused by failed wells' sealing systems, their reduction potential, and associated abatement cost.

Targeted methane influxes occur due to failed wells' sealing system and unwanted inflow of reservoir fluid from the formation into the wellbore. Reservoir fluid is a mixture of oil, natural gas, and water, which is delivered to a surface and shall be treated before further transportation (Speight, 2016). Methane (CH_4) is the largest component of natural gas (The U.S. Energy Information Administration (EIA), 2021). Reservoir fluid moves to the lower pressure areas, first wellbore, and next surface. Figure 1 demonstrates a pressure gradient in the typical well. Methane as gas makes its way into the wellbore if any microchannels or cracks exist in the well-sealing system.

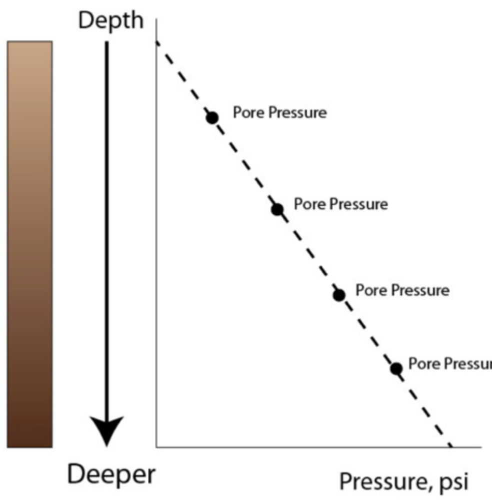


Figure 1:Pressure gradient in the wellbore.
Source: (Drilling formulas, 2015)

In Section 6.3, the study provides an overview of the well construction process to introduce a reader to the well integrity concept. The targeted group of emissions could be the easiest to reduce since no capital costs are required, unlike the on-site gas utilization (e.g., liquefication plant construction), which requires significant capital expenditures. Many on-site gas disposal methods are not suitable for Russian projects. For example, a vapor recovery unit (VRU) suggested measured to mitigate methane venting (The Climate and Clean Air Coalition (CCAC) Oil and Gas Methane Partnership, 2021), mainly due to long distances, and lack of infrastructure, such as gas pipeline. A VRU is installed on each wellhead to collect otherwise emitted methane. The gas is then collected, processed, and sent to the main gas pipeline for onward delivery to the refinery or the end-user. The main feature of Russian oil and gas fields is their remoteness and not all oil fields have an access to the gas line. Thus, to utilize VRU a company will have to invest in building of several thousand kilometers pipeline to enter the collected gas into the transportation system.

The study estimates the possible reduction of methane emissions caused by well integrity failures, utilizing available remedial technologies. Tackling the targeted methane emissions makes good financial sense, as restored well integrity provides the following benefits: increased oil output, reduced operating costs, resource conservation, improved air quality, and protection of aquifers from contamination.

Well integrity is essential for the safe production of oil and gas and to ensure that operations are environmentally sound throughout the well lifecycle. A new well can be designed and constructed with a reliable sealing system, preventing the wellbore's unwanted flow of reservoir fluid. Many of the problems that contribute to integrity issues, such as cementing and casing deformation, can often be addressed at the well design phase thus preventing lost production. There is a great amount of value in ensuring that you have your well integrity from the start. It starts with proper design, proper connection makeup, proper cementation, proper planning, and centralization. For some operators, the cost reached 260 million US$ for a delayed production due to a well integrity issue where they had to bring in a workover rig, pull out completion and rerun it - Scott McIntire, Weatherford. (Walzel, 2020)

Over the last decade, on average, more than 5000 wells a year have been drilled, completed, and commissioned into production in Russia (TMK Group, 2020). Each year the complexity of the wells increases. Oil wells will become deeper, with extreme trajectories, aggressive downhole environment (high reservoir pressure, presence of CO_2, H_2S, temperature), simultaneous exploitation of several layers of formations. Changes in well design may increase the risk of unwanted wellbore gas inflow, which will eventually channel to the surface. Thus, the integrity of the well shall be the highest priory of an oil-producing company, starting from the well-designing stage.

Failure of the sealing system in mature wells is a common scenario. However, even when the leakage is confirmed, it does not mean that the well should be killed and secured immediately. The risks of continuing the operations shall be evaluated, and the well must be put under close surveillance (Wellcem, 2019). At the same time leaving leaking wells untreated potentially leads to continuous methane emissions and potential accidents, such as the “Deepwater Horizon oil spill” (National Commission on the BP Deepwater Horizon Oil spill and offshore drilling, 2021). Well’s sealing system remedial measures do not require the construction of additional facilities on the field site; thus no capital expenditures. On top of that, by reducing the downhole leakages, infrastructural methane emission can also be prevented to some extent. A concerning problem is the lack of data for estimating the possible emission reduction. For example, there is no statistic on the number of oil wells with the compromised sealing system. This is because the well's sealing system is not a parameter or production technology, it is more a condition of the well and is not yet being monitored in Russia. The next challenge is the volume of the emitted methane, both deliberately ventilated and fugitive. Ventilated gas is technically possible to measure (Calscan Solutions INC, 2021), and yet it appears that there is no available data for Russian wells. Although the well's barrier system failures are common, their forecasting method, or where, in what shape and when such failures occur, do not exist. One well can have several sealing non-perfections, different forms, sizes and located at different depths of the wellbore. The existence of several different non-integrities in one well makes it difficult to estimate the average cost of repair.

Chapter 2. Research design

Methane emissions were always a problem for oil and gas producing companies from the health and safety perspective. In Russia, starting from the early 1990s, methane has been treated as a pollutant, and companies are obliged to pay fines based on the emitted values; as of 2018, the rate was 108 RUB (1.4 US$ at the current exchange rate 1.04.2021) for one ton of emitted methane beyond the allowed level (Goverment of Russian Federation, 2016). Recently, the global warming problem and methane's ability to absorb energy have attracted much public attention to methane emissions, particularly for oil and gas industry. Russia has ratified the Paris Agreement, thereby targeting to limit greenhouse gas emissions by 2030 to 70 per cent relative to the 1990 level (UNFCCC, 2021). Methane may be treated as GHG, not only a pollutant, and in this case, companies may face double fines unless the Government will adopt the legislation.

The aim of this study is dual. The first goal is to assess the possible reduction of methane emissions caused by the failure of initial well insulation (or well integrity). The second objective is to understand the costs of required repair measures and investigate whether remedial actions are feasible. The focus area of the research is oil wells in Russia, located onshore, targeting conventional resources. Suggested topic main advantages are as following: first, focusing on emission point – wellbore emissions caused by well integrity losses. Second, mitigation of the certain type of emissions may be beneficial for oil-producing companies due to extended life expectancy of the well and better onsite safety. Lastly, integrity remedial measures do not require capital expenditures, unlike some onsite methane treatment measures such as the installation of Vapor Recovery Unit (VRU) (United States Environmental Protection Agency, 2021). Targeted wells in Russia have several specifics, e.g., remote location, extreme weather conditions, and lack of access to major infrastructure, such as electric grids, gas or pipeline and roads. The mentioned qualities must be taken into consideration when appropriate remedial technology is selected. Some researchers have mentioned well integrity failures and related methane emissions (Kubrak, 2012), (Yurkevich, Michurin, & Yurkevich, 2019). However, to the best of my knowledge, no study has explicitly looked at methane emissions caused by well-integrity losses in Russian oil wells. That fact makes the present report unique and novel.

The study begins with determining the percentage of leaky wells. The report of M.G. Kubrak focuses on the problem of idle (inactive) wells at the projects of "Samotlorneftegaz" an open joint-stock company (OJSC). The author finds that 37% or 116 wells out of total idle wells are out of operations due to the casing pipes integrity breach (Kubrak, 2012). Industrial periodicals or annual industry reports publish information about the oil well stock in Russia for example (Filimonnova, Nemov, & others, 2018). The most comprehensive and detailed study of methane emission from wells with integrity issues found is “A portrait of wellbore leakage in northeastern British Columbia, Canada.” (Wisen, et al.). This study examined the wells' share with reported leakages and concluded that out of 21,525 wells tested for leakage, 2,329 (or 10,8%) reported some integrity issues (leakages).

The central theorem of this study assumes that existing technologies could mitigate methane emissions caused by well integrity failures. The document aims to compare actual volumes of methane emissions and the potentially reduced volumes of emissions by implementing existing well integrity restoration technologies.

The assessment of methane emissions potential reduction will require the identification of the following parameters. First, a total number of oil wells in Russia; wells which are currently in operation and temporally inactive wells. Information about well population is published annually in industrial periodicals such as (Filimonnova, Nemov, & others, 2018). Next, the share of oil wells with integrity issues needs to be determined. As mentioned above, no similar studies covering the Russian well stock were found. Data from several studies will be used to assess the share of wells with leaks. One report provides a global average share of wells with leaks as 19% (Normann, 2019). Two studies have been conducted to understand the share of wells with integrity issues on the Norwegian shelf. One study by Norwegian: Stiftelsen for industriell og teknisk forskning (SINTEF) in 2007, concluded that out of a total of 227 wells under review, 25% had at least one reported leak. The second study was conducted in 2006 by the Norwegian Petroleum safety authority; the study’s results were 18% of the total observed 406 wells had reported integrity problems. The other interesting finding of the study was that newer wells presented more integrity problems than older ones (SINTEF Petroleum research, 2021). In the study (Wisen, et al.), the share of wells with reported integrity issues was 10.5% out of the total well stock for British Columbia, Canada. Since no data is available for the share of wells with integrity issues for Russia, industry experts were surveyed to estimate the percentage of the wells' with the breached sealing system.

Next, the value of methane vented from wells with integrity issues needs to be estimated. This parameter is the most challenging as no data on direct measurements in Russia is available for public use. The mean reported casing flow rate (methane emissions ventilated from casing annulus) in the study (Wisen, et al.) is 5.9 m3/d per well, which corresponds to a mass rate of

3.87 kg/d and per well or 1.4 t/y per well, assuming that the exiting gas is composed entirely of methane.

A separate chapter of the study discusses types of integrity failures and possible reasons that stand behind them, so that the reader can have a general idea of the issue. It is essential to highlight that a well with integrity losses is a very complex issue as one well can have several leaks and each may require a different approach and different repairing technologies. There is no one unified recipe for treating a well with methane leaks, as each well is unique. However, most of the wellbore leakage points could be identified, and most of them could be repaired. The main issue is the high repairing cost of some severe cases and the economic feasibility of such operations. Technologies for both identifications of leakage and repair exist. Moreover, increased attention to methane emissions in oil and gas has led to new enterprises and research and development projects targeted to solve the problem. In Figure 2, a schematic flow of the study is presented.

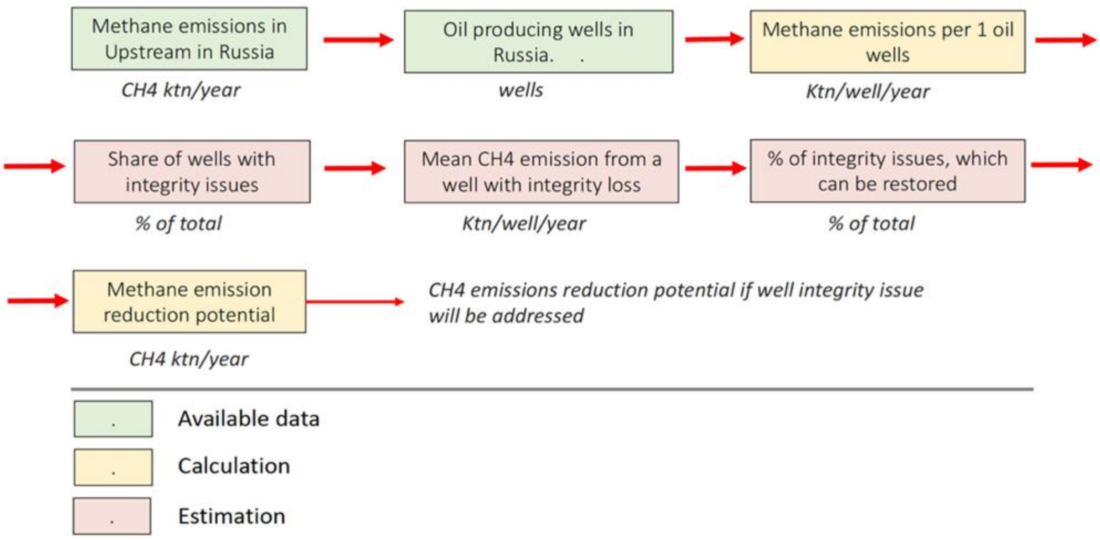


Figure 2: Research scheme

Chapter 3. Methane emissions and climate change

Section 3.1. GHG emissions and role of methane

Methane is the second most important greenhouse gas, after carbon dioxide (CO_2), with global warming potential 25 times higher than carbon dioxide per ton gas released and when using a 100 year time-perspective (Forster & Ramaswamy, 2007) . The concentration of methane in the atmosphere is 150% above the pre-industrial level, Figure 3 (Global Carbon Project, n.d.). The increase in emissions, Figure 3, can be explained with introduction of fossil fuels at the beginning of the Industrial Revolution around 1750. Oxidation of methane is responsible for a large fraction of the ozone formation in the troposphere (Michael Sanderson, 2021). Ozone (O3) in troposphere is an important greenhouse gas and air pollutant, which is harmful to both humans and ecosystems. It is also a major component of urban smog. (Climate & Clean Air Coalition, 2021).

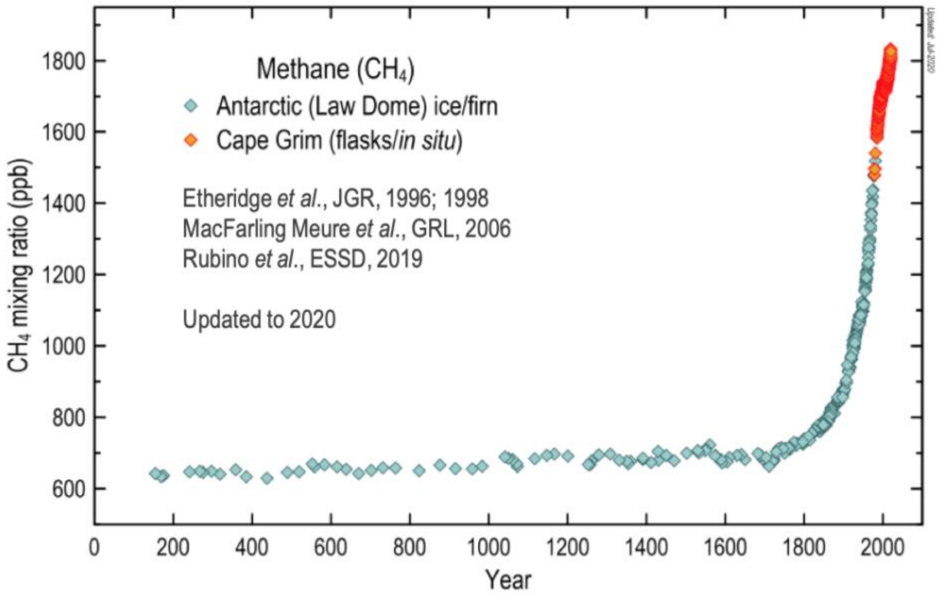


Figure 3: The concentration of methane in the atmosphere
Source: (Global Carbon Project, n.d.)

Section 3.2. Anthropogenic and natural methane emissions

Methane emissions can be both natural and anthropogenic. The Global Atlas project estimates methane emissions from wetlands as 149 Mt CH4 a year on average during the decade 2008–2017. Figure 4, demonstrates the geographical distribution of methane influxes (Global Carbon Project, n.d.). Anthropogenic sources are responsible for about 60% of global emissions. Largest emissions are found in South America, Africa, South-East Asia, and China (reportedly 50% of global emissions).

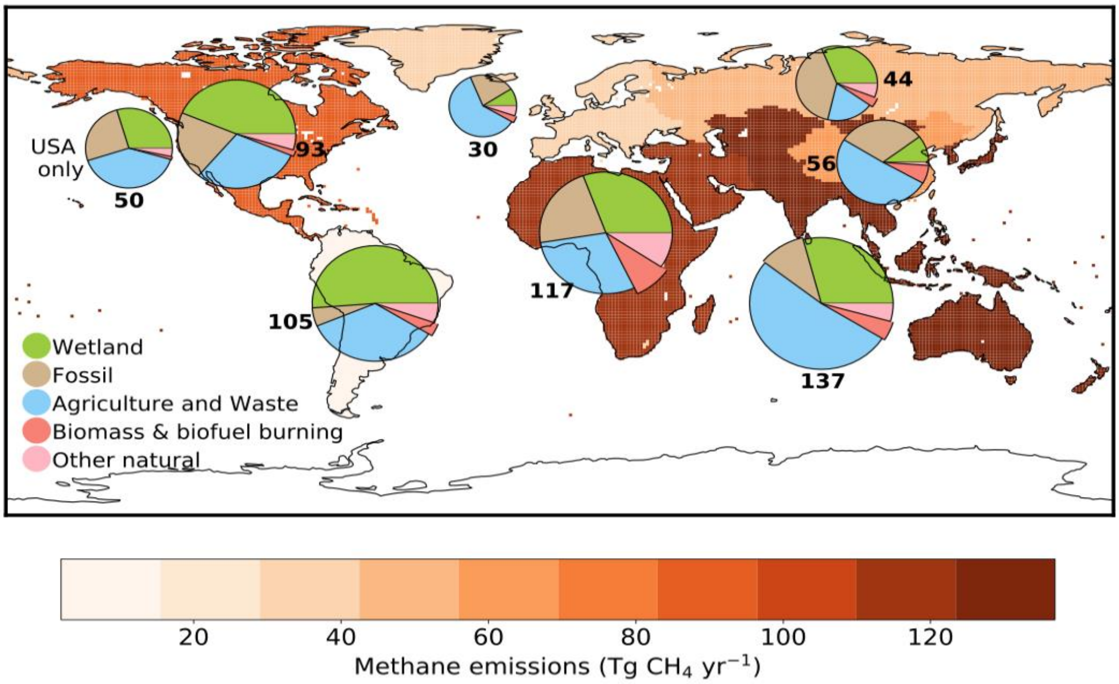


Figure 4: Geographical distribution of methane emissions
Source: (Global Carbon Project, б.д.)

Section 3.3. Values of anthropogenic methane emissions

Section 3.3.1. Detection and measurement technologies

There is no one independent, international body exists that collects and verifies methane emissions data. According to the EU Methane Strategy, EU commission in cooperation with the UN Environmental Program (UNEP) have announced the creation of International Methane Emissions Observatory (IMEO) aiming to engage with governments and companies worldwide to accelerate reductions of methane emissions globally (Caltagirone & Piebalgs, 2021).

There are two widely used methods of estimating methane emissions from natural gas operations. First is the bottom-up (BU) approach, which involves direct measuring of individual methane emitters, such as an oil well or landfill, and then extrapolating those results to similar sources on regional and national scales, including emissions factors, activity data, and process-based models (National Academies of Sciences and others, 2021). In contrast, the top-down (TD) approach estimates emissions using observations of atmospheric methane concentrations. This can be performed at a regional scale, for example, flying an aircraft upwind and downwind of a study area. Top-down and bottom-up techniques are both needed and complement each other.

New technologies are emerging, aiming to detect and measure methane emissions with high accuracy to identify the source. For example, MethaneSAT is designed to locate and measure methane from human sources worldwide, giving both companies and governments the power to track, quantify, and liquidate those emissions. Currently, MethaneSAT is at the advanced stage of development and scheduled for launch in October 2022 with Space X (Mathewson, 2021). However, more initiatives are needed to transform derived by satellite concentrations into the user-friendly information sets. Such solutions are expected to be developed in the next couple of years, 2023-2027 (EVIA, 2020).

The UNFCCC and Carbon Atlas publish methane emissions volumes, however reported emissions values are not always consistent. There appears to be discrepancies in values due to the different methods of assessments. It is not a surprise that if it is difficult to understand global methane emissions, it is even more challenging to identify emissions related to one industry and belonging to the specific geographic area. In the next Section 3.3.2, existing information sources of methane emissions will be discussed, and information discrepancies will be addressed.

Section 3.3.2. Methane emissions data sources

The Global Carbon Project uses an inverse technique to assess atmospheric concentrations of methane. Inverse model links bottom-up (BU) emissions estimates to top-down (TD) methane measurements in the atmosphere. This model provide estimates of methane fluxes consistent with atmospheric methane concentration measurements but depend on an atmospheric transport model choice (Global Carbon Project, n.d.). The Global Carbon Project recently estimated average annual methane emission during 2008-2017 at 576 Mt CH4 a year top-down approach (TD) and 737 Mt CH4 a year for bottom-up approach (BU).

Another source for methane emissions data is the national inventory reports (NIR). Under the United Nations Framework Convention on Climate Change (UNFCCC) countries ratified Annex-1 of the convention, including Russia, must report GHG emissions annually. Countries, which are signed up as non-Annex 1 are obliged to submit their first Biennial Update Report (BUR) by December 2014 and every two years after that. Figure 5 presents the methane emissions from Annex-1 countries in 2017.

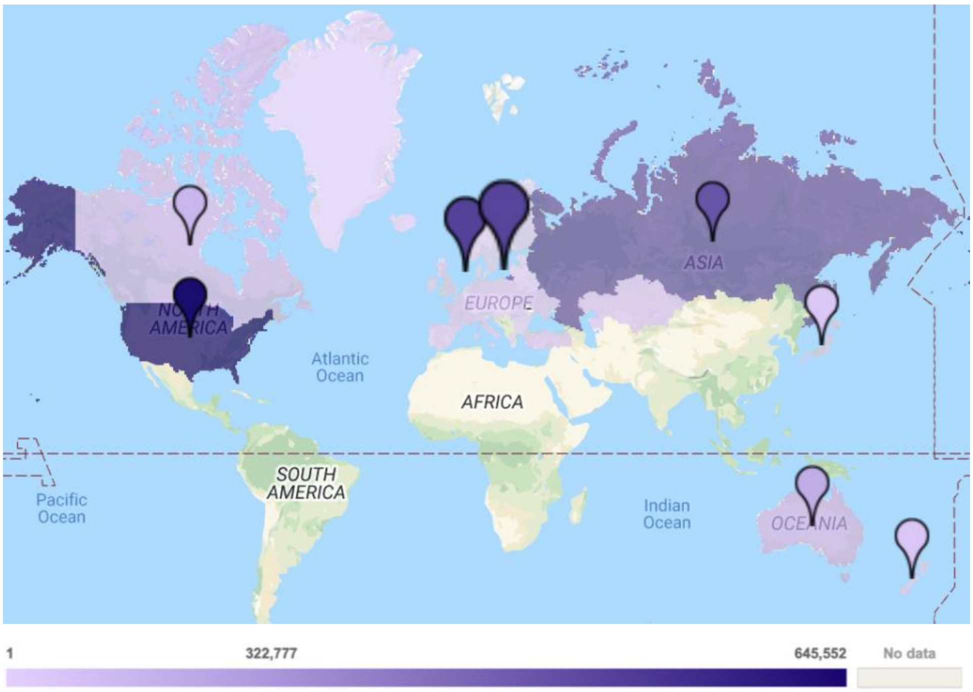


Figure 5: Methane Global emission map, Annex -1 countries (2017) UNFCCC
Source: (UNFCCC, 2021)

The Copernicus Atmospheric Monitoring Service (CAMS) provides information on air pollution and health, greenhouse gases, and climate impacts worldwide. Copernicus uses satellite Earth observations, in situ (non-satellite) data, and simulations. Figure 6 shows that the highest methane concentrations are found over Southeast Asia (Copernicus Atmosphere Monitoring Service, 2021)

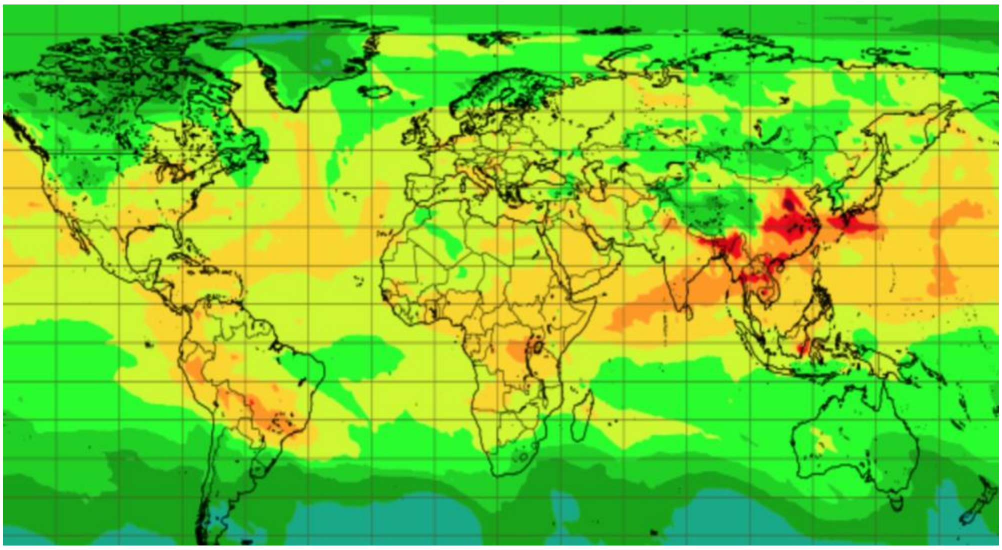


Figure 6: Total concentration of methane in the Atmosphere [ppbv]
Source: (Copernicus Atmosphere Monitoring Service, 2021)

Section 3.4. Methane inventory in Russia

According to the Russian legislation, methane is considered a pollutant, and companies are obliged to pay fines for each emitted ton of methane above permissible emission rate (Goverment of Russian Federation, 2016). Legal entities must report methane emissions annually; however, there are no requirements for measuring techniques. Therefore, reported emissions are usually "best-guess" or estimations made by companies and not based on actual direct measurements. Direct measurements of emissions from different sources, especially remotely located, are yet too expensive and labor intensive. Enterprises submit recorded methane emissions values to federal statistic agency annually until January 22 of the following year. The completed forms with methane emissions are approved and signed by the management of the organizations. National emissions fines are based on companies' emissions reports.

In addition to the national regulations, Russian Federation is an Annex-1 party of UNFCCC. Under the convention's conditions, the Russian Federation annually submits GHG inventory report. The latest UNFCCC report was published in April 2019, the last reporting year was 2017, base year 1990. Figure 7 presents schematically emission data collection process in Russia. Reported emissions for every party of the convention are conveniently organized and openly available at UNFCCC web page (UNFCCC, 2021).

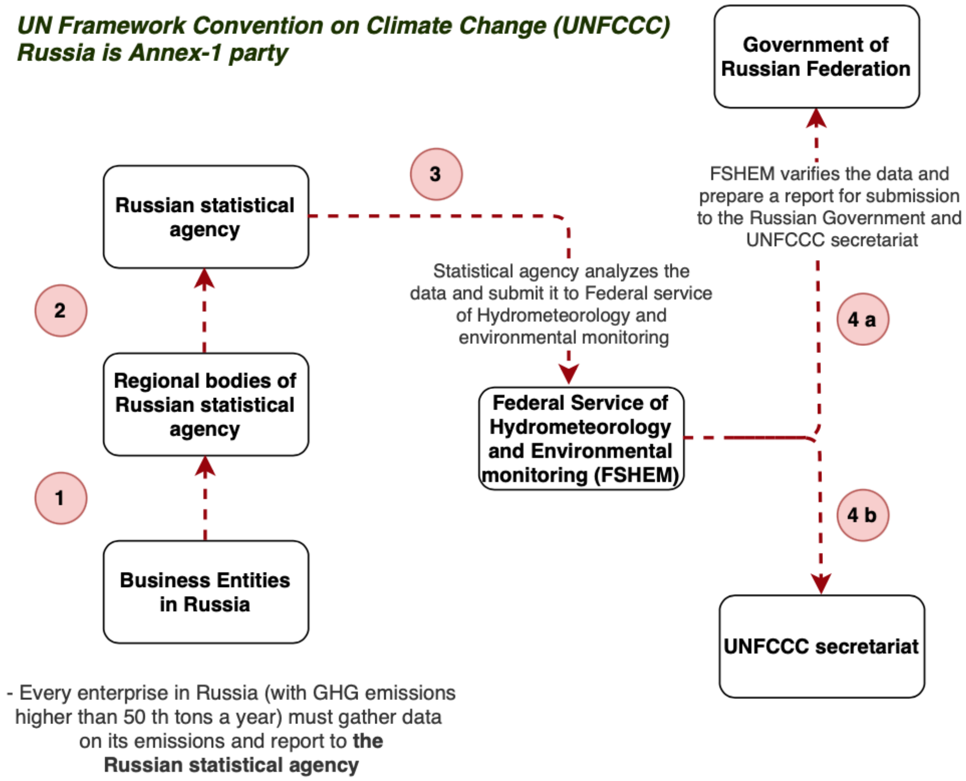


Figure 7: GHG emissions reporting process in Russia

Section 3.5. Methane emissions related to oil and gas industry

The use of fossil fuels must be gradually phased out to meet the Paris Agreement's climate goals. World Energy Outlook's Sustainable Development Scenario (SDS) project that oil demand would have to decline by 3 mb/d between 2019-2025 (IEA (International Energy Agency), 2021). Therefore, it is important to reduce immediate environmental impacts associated with producing and consuming fossil fuels. Lack of data on emissions values is one of the major obstacles of preventing the development of efficient mitigation strategies. In recent years many efforts have been invested into methane emissions data improvement. International Energy Agency (IEA) has recently launched the Methane Tracker initiative. Methane Tracker is an online platform where the most recent and relevant information on methane emissions can be found. Methane Tracker provides a comprehensive picture of methane emissions across more than 70 countries – as well as mitigation measures (IEA (International Energy Agency), 2021).

Section 3.5.1. Global oil and gas related methane emissions

Figure 8 presents global oil and gas related methane emissions by different informational sources. Values vary from 63 Mt CH4 a year (Schwietzke et al. 2016) to 91 Mt CH4 a year, estimated by the U.S. Environmental Protection Agency (EPA). There is no information on global emissions reported to UNFCCC, possible reason that not all countries have ratified the convention. All Annex-1 countries report detailed estimates of oil and gas sector emissions. Among countries not reporting methane emissions to the UNFCCC is Saudi Arabia, the third largest oil producer in the World as of 2019 (Statista, 2021).

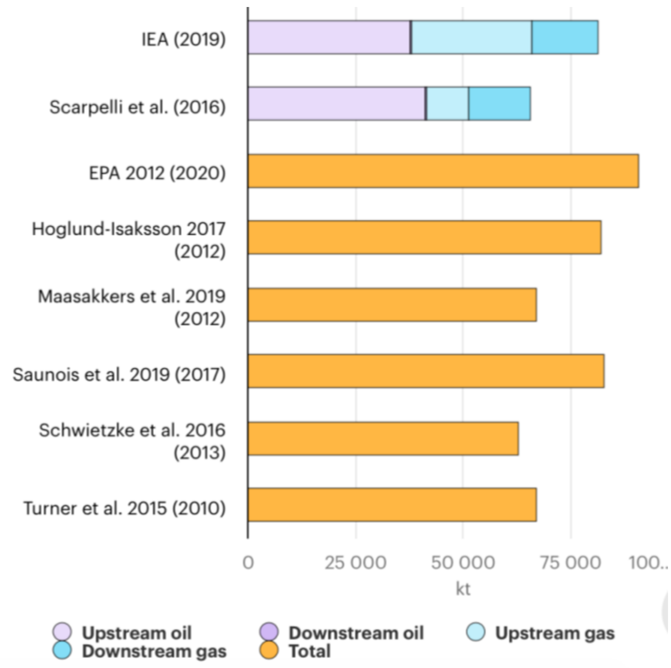


Figure 8: Global Oil and Gas related Methane emissions (different sources of information) Source: (IEA (International Energy Agency), 2021)

The Norwegian Environment Agency (NEA) in close collaboration with industry and government agencies conducted a two-year study (2014–2016). The finds that the existing (old) methodology for quantifying emissions was incomplete. Forty-eight potential sources of cold methane ventilation and fugitive emissions were identified, which is more than the 13 previously reported by operators. Revised emissions levels were lower than previous estimates, but there were considerable variations between emission sources. The emission abatement potential was found to be around 10%. (Norwegian Environment Agency (NEA), 2021).

In the US, the Environmental Protection Agency (EPA) collaborates with many experts and institutions in preparing its annual National Inventory Report (NIR) for the UNFCCC. The EPA obtains information and data related to emission estimates through greenhouse gas emissions reports. The new data was recently incorporated into US estimates for all oil and gas supply chain segments.

In Canada, Environment and Climate Change Canada (ECCC) uses a variety of data from industry and provincial/territorial governments and works actively to improve the methods and data used to prepare emission estimates. For example, in the latest country's NIR submitted to UNFCCC, methane emissions from abandoned oil and gas wells were estimated. Abandoned wells were categorized (plugged, unplugged) and counted in each county. The emission factors were taken from a study "Emissions of Coalbed and Natural Gas Methane from Abandoned Oil and gas wells in the United States" (Townsend-Small, Ferrara, Lyon, Fries, & Lamb, 2021) since, there are currently no emissions data on abandoned wells in Canada (Pollutant Inventories and Reporting Division, 2020).

In 2016, the Ministry of Energy of the Russian Federation initiated a study to develop and update national emission factors for oil and gas systems based on national statistics, measurements and analysis. The country-specific emission factor has been revised and used as the basis for the 2019 UNFCCC emission data. As a result the reported methane emissions in the Russian oil and gas sector in 2010 decreased from 23.6 to 6.5 Mt CH4 in 2017. This large difference indicates that the uncertainty in these estimates is still high. The emissions reported in 2019 will be used for the analysis in this study (UNFCCC, 2021).

Levels of oil and gas production and methane emissions were compared across the leading oil and gas producers. Russia is within the top producing countries. In 2019, according to Enerdata (Global Energy Statistical Yearbook 2020, 2021), Russia was the second-biggest oil producer and second-biggest gas producer. Table 1 presents oil and gas production values and values of reported methane emissions and estimates methane emissions per ton of produced oil.

Table 1: Oil and gas top producers and related methane emissions

Country	2019 Oil production Enerdata		Methane emissions IEA estimations		Methane emissions reported to UNFCCC	
	[mln ton]	% of total	[mln ton]	Methane emissions per each produced ton of oil (tons)	[mln ton]	Methane emissions per each produced ton of oil (tons)
United States	745	22%	11,4	0,0153	7,4	0,010
Russia	**560**	**17%**	**12,4**	**0,0221**	**6,7**	**0,012**
Saudi Arabia	545	16%	3,4	0,0063	no reports	no data
Total World	**3348**	**100%**				

Source: Enerdata & IEA Methane Tracker 2020 & UNFCCC & (Roshydromet, 2019)

Table 1 indicates that the US is producing oil and gas with lower emissions per unit of oil and gas produced compared with Russia. However, both countries are reporting to UNFCCC lower emissions than estimated by the IEA, which could indicate underreporting of emissions in both Russia and the US.

Section 3.5.2. Oil and gas related methane emissions in Russia

A national GHG inventory report (NIR) is published by national authorities (Roshydromet, 2019) and by UNFCCC annually (UNFCCC, 2021). This report is publicly available and provides comprehensive data on GHG emissions in Russia. However, published emissions are not an independent estimate but based on the reports from local enterprises and verified by responsible Russian agencies. It contains emissions values, derived directly from emitters (enterprises) in Russia. Self-reporting is not the most reliable and accurate measure to assess actual emissions, yet it is the only option is currently available now. Russian oil-producing companies, for example, JSC Rosneft, issue an annual sustainability report, where emissions values are published as well as mitigation actions reported (JSC Rosneft, 2021).

Section 3.5.3. Targeted methane emission group

A certain group of methane emissions is the target of this study. Methane emissions occurring due to breached sealing system of the well. Emissions can take two forms: first is surface casing vent flow (SCVF) and second is gas migration (GM) (Gallardo, Li, Morais, Phillips, & Riley). Estimated emission reductions are limited to onshore oil wells in Russia.

Required value of methane emissions is published in the National Inventory Report (NIR) (Roshydromet, 2019) under the category "Oil and venting" and for 2017 is 462 kt CH4 a year (Roshydromet, 2019). NIR's venting group includes all methane emissions generated during production, including drilling, production (all downhole operations to bring the crude oil to the surface), and emissions generated from on surface operations, like on field transportation (gathering system), produced oil treatment (such as degasification), and storing operations. The study targets the emissions only related to the well-sealing system's failures; such emissions come directly from the wellbore or the wellbore area. The IEA inventory does not provide detailed information about the sub-sector "oil, venting" specifically and therefore the information from the Russian NIR will be used for the study.

Table 2: Methane emissions open by group and source of information

Parameter		Kt CH4	Information source
Global	Global Methane Budget	358.000	Global Carbon Project (TD), including China
Global	Global Methane Budget (Anthropogenic)	157.214	UNFCCC reports (excluding China)
Russia	Total Methane emissions reported by Russia (all sources)	16.305	National GHG Inventory report
Global	Methane emissions associated with oil and gas industry	37.123	UNFCCC reports
Global	Methane emissions associated with oil and gas industry	81.525	Methane Tracker (IEA), 2019
Russia	Methane emissions associated with oil and gas industry	6.687	National GHG Inventory report
Russia	Methane emissions associated with oil and gas industry	12.361	Methane Tracker (IEA), 2019
Russia	Targeted methane emissions group (oil, venting)	462	National GHG Inventory report

Source: Global carbon project & UNFCCC & IEA Methane Tracker 2020 & (Roshydromet, 2019)

Chapter 4. Methane emissions from oil and gas industry

The decision to prioritize the production of oil over natural gas production may depend on several factors. First is the structure of the reserves. Oil reserves often contain natural gas (US Energy Information Administration, 2021). The reservoir contains both oil and gas. The production target depends on economic feasibility and, in the case of Russia, the infrastructure availability. At the initial stage of the field development, oil could be shipped by trucks and after by train. Even in the projects target to produce oil, associated gas and methane emissions are unavoidable side effects.

Detection and quantification of methane emissions requires a combination of operational measurements and calculation-based methods. An obstacle of mitigating emissions is the vast number of emissions points: Each field may include from a few to several hundred emissions points. Emission points could also be geographically dispersed, and methane emissions can be spread across several locations, increasing the costs measurement. Next Sections, review possible methane emission points across the major segments of the industry, upstream, midstream, and downstream (Energy HQ, 2021).

Section 4.1. Fundamentals of methane presence in oil producing wells

Petroleum is made up of hydrocarbons and was formed millions of years ago. First, bacteria and chemicals destroyed organic material and created layers of the sediments. Then heat and pressure turn the organic matter of sediments into the oil. The pore system in the rock allows the oil to migrate (V.P. Dimri, 2012). Throughout time, the formation's forces are balanced and set the formation's pore pressure, which is the main source of energy for moving fluids through the formation. Gravity causes the fluids to separate according to the fluids' density, so the typical order of fluids in the formation is gas at the top, oil, and then water at the bottom. Oil reservoirs can be classified as saturated and undersaturated reservoirs (V.P. Dimri, 2012). In saturated oils, gas begins to come out of the solution as soon as the reservoir pressure begins to decrease, but in the case of unsaturated oil, the dissolved gas does not start coming out of the solution until the reservoir pressure drops to the level of the bubble point. The presence of a gas cap in a reservoir always indicates saturated oil (Figure 9).

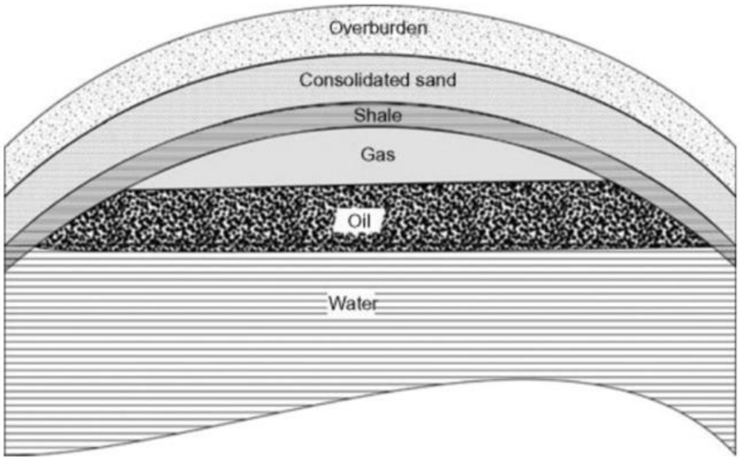


Figure 9 Reservoir structure example
Source: (V.P. Dimri, 2012)

Pressure in a well usually is higher the deeper the well (Schlumberger, 2021). When a well is drilled, a potential vertical path is created for reservoir fluid to move first to the wellbore and next upwards to the lower pressure zone. Well construction aims to allow only certain fluids to move upwards for production, for example limiting gas or water production. However, gas is much lighter than oil; thus gas or methane will be the first to move upwards. A properly constructed well allows certain fluids up to the surface under controlled conditions and only for a specific time.

Section 4.2. Emissions in oil and gas across the industry supply chain

Methane emissions can occur across the whole supply chain of the oil and gas industry, starting from discovering the field to combustion. The oil and gas industry is usually divided into three blocks: Upstream, Midstream, and Downstream (Energy HQ, 2021). The current chapter overviews the possible methane releasing points in each block.

The Upstream segment includes processes related to the exploration and production of oil (finding oil and bringing it upwards to the surface), including drilling, well construction, production, and the on-site system of produced fluid gathering and preparation (Investopedia, 2021). Generally, upstream methane emissions can be divided into three major groups: first, methane releases, ventilated or leaked around the well area due to poor well integrity; second, gas leaked or deliberately discharged from the surface product gathering system and third, methane releases occur due to the incomplete combustion. This study main focus is methane emissions in the Upstream sector and particularly methane emissions caused by well insolation system failure (well integrity failure).

The ‘Midstream’ segment includes processes required to store and transport crude oil to the refinery, such as pumping stations, tank trucks, rail tank cars, and transcontinental tankers (Energy Education, 2021). The midstream industry generates GHG emissions, including methane from compressor engine exhausts, oil and condensate tank vents, and natural gas processing units. Mobile sources such as ships, railcars, and trucks for material transport, planes/helicopters, and other company vehicles for personnel transport are the other significant sources of emissions in midstream.

The “Downstream” segment covers everything involved in the process of turning crude oil into finished products, like diesel, jet fuels, heating oils, and asphalt for building roads, as well as synthetic rubbers, fertilizers and preservatives. Just about anything that is manufactured has some connection to oil and gas.

The Upstream accounts for a significant share of methane emissions. Following the report “Best Practice Guidance for Effective Methane Management in the Oil and Gas Sector” (United Nations Economic Commission , 2021) Upstream is responsible for 72% of global oil and gas emissions or 77% (Figure 10) in ECE member states (Nations Economic Commission for Europe, 2021).

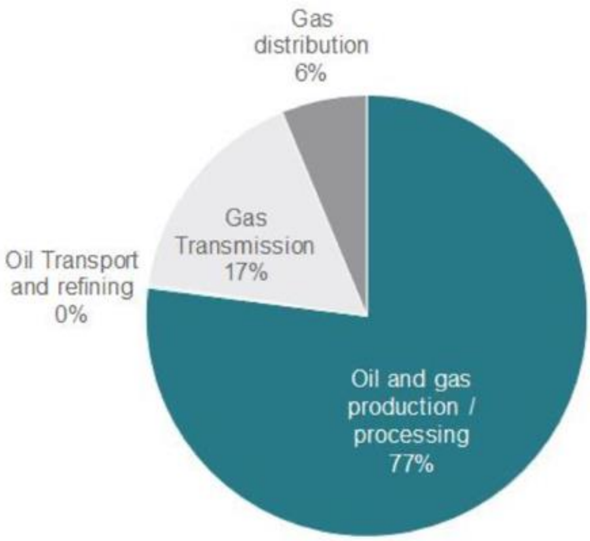


Figure 10: Breakdown of oil and gas methane emissions by segment, ECE member states
Source: (United Nations Economic Commission , 2021)

Chapter 5. Methane emissions points in oil Upstream segment

Methane emission points of the Upstream segment must be located to help to understand the research area. Methane releases (ventilated or fugitive) occur across the entire Upstream segment, starting from the drilling to the on field product gathering system. In this study, upstream methane releases are separated into several groups. Some emissions are accidental (fugitive), for example, emissions from failure of seal or leaking valve, while others are deliberate, often carried out for safety reasons or due to the facility's design or equipment.

Section 5.1. Associated petroleum gas (APG)

Natural gas produced as a side product during crude oil production, is referred to as Associated petroleum gas (APG). This gas exists either separately from oil in the formation or dissolved in the crude oil. APG may contain impurities such as hydrogen sulfide (H2S) and carbon dioxide (CO2). APG cannot be used onsite or transported without pre-treatment. In some cases (particularly remote locations or onshore), such unwanted gas is vented or flared. Due to increased environmental consciousness and energy demand, flaring is prohibited, limited, or strictly regulated in most countries, including Russia. There are several options for using APG, for example, injecting gas into an oil reservoir to increase production. Alternatively, APG can be used for on-site power generation and heating. On-site APG usage is common in Russia, and around 5% of produced APG is flared. In Russia, it is legally binding to utilize at least 95% of totally produced APG, moreover, recently the Russian Ministry of Natural Resources suggested increasing the APG on-site utilization share to 97.5% (Kommersant , 2020). There are several technologies of on-site utilization such as mini-LNG or underground gas storage.

In 2020, Russian oil-producing company JSC "Rosneft" introduced underground APG storage facilities on Verchnechosnkoe oil field. As part of the project, all required infrastructure was constructed at the field, including a gas compressor station, a 40 km long gas injection pipeline, and a well pad with six wells for APG injection. The cost of the project was approximately 140 mln US$ (8.7 bln RUB) for only one oil field. (JSC Rosneft, 2021). In addition to that, downhole measures can be utilized to reduce the value of produced APG, for example, downhole inflow control measures in some cases could reduce the share of produced APG up to 85% (InflowControl, n.d.).

Section 5.2. On surface methane emissions in Upstream segment

The second group of emissions in the upstream oil segment is associated with on surface field infrastructure. The produced reservoir fluid or crude oil is a mixture of oil, gas, water and other substances requires treatment (such as gas separation and more) for further usage and transportation via gathering system (Appendix 2). Gathering pipelines on the field deliver the produced fluid from the source (or well) to the processing unit or storage tank, Figure 11. Methane emissions are possible at any point of infrastructure, including, but not limited to, valves, flanges, gathering pipelines connections, pumps, compressors, pressure relief devices and process drains system degassing vents (Energy Institute, Colorado State University, 2021). Once a leak starts, it tends to remain a continuous source of emissions until repaired. Regular leak detection measures are required to repair or replace equipment with cracks and decrease methane discharges. Close-range methods such as optical gas imaging are essential for the leak detection at on surface infrastructure, however, it is labor-intensive and expensive, particularly for remote locations with difficult access. Today, several alternative methods of leak detection are emerging, such as handheld instruments, fixed sensors, mobile ground labs, aircraft, and satellites. (Thomas A Fox; Thomas E Barchyn; David Risk; Arvind P Ravikumar; Chris H Hugenholtz, 2021).

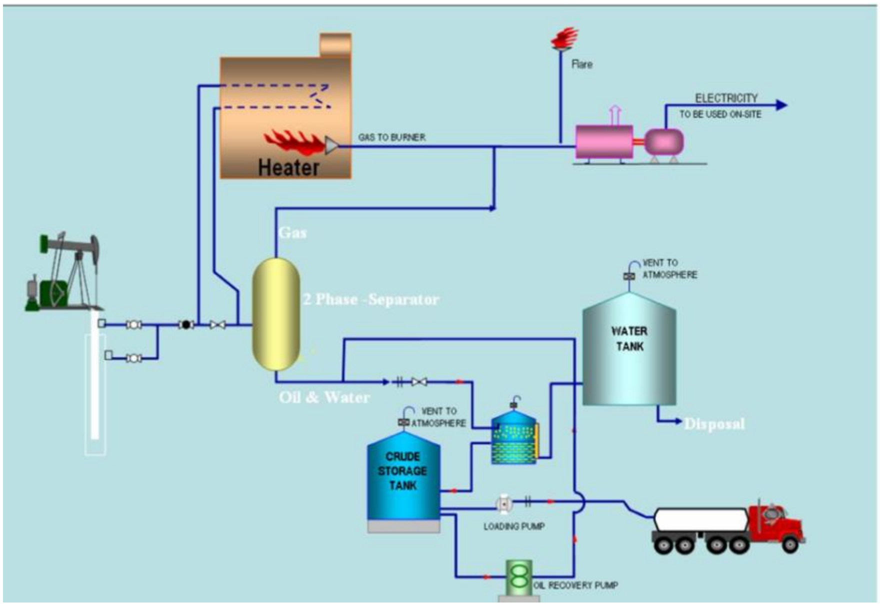


Figure 11 Crude oil onsurface production process (exluding downhole operations)
Source: (4.bp.blogspot, 2021)

Section 5.3. Wellbore methane leakages

The term Wellbore leakage refers to an accidental hydraulic connection between geologically isolated zones and the wellbore, due to defects in its design or non-conformances during construction (Wisen, et al.). Wellbore leaks can contaminate the groundwater and contribute to GHG. Possible paths of wellbore leaks are presented in Figure 12. Wellbore methane leaks also could be called gas migration, gas seepage, behind-the-casing leakage. Major factors affecting wellbore leakages are geological conditions, well design, internal or external corrosion of casings. Well leaks can be detected and repaired, with existing technologies. The most significant advantages of targeting the well integrity are ease of implementation and relatively low costs.

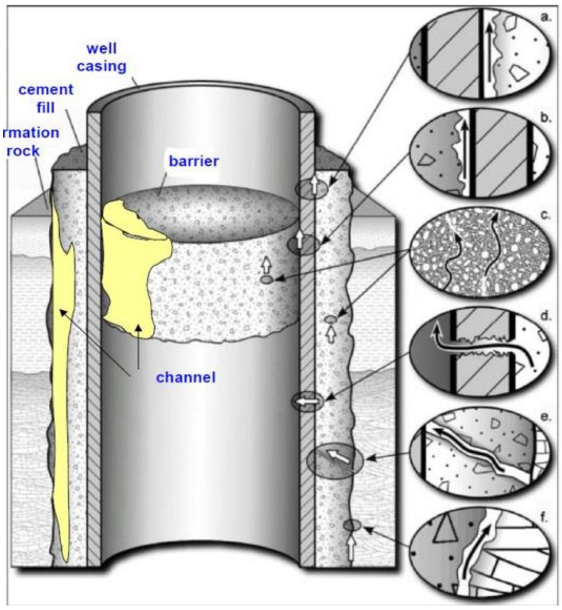


Figure 12 Possible paths of wellbore methane leakages
Source: (Celia, Bachu, Nordbotten, Kavetski, & Gasda, 2005)

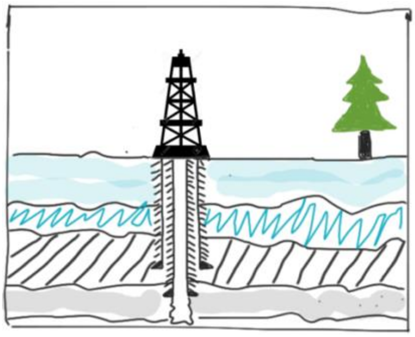
Chapter 6. Well integrity introduction

Section 6.1. Life cycle of oil well and integrity

An oil well is a hole in the earth dug through different geological formations (including ones containing gas and water), intending to produce oil from the targeted formation (Energyeduction, 2021). Several barriers shall be constructed to ensure the well stability, prevent borehole from collapsing and limit the inflow of the unwanted formation fluid to the wellbore. Well barriers can be a structural steel pipes, cement shear or mechanical. A sealing packer (inflatable or swellable) (TAM International, 2021) is an example of a well mechanical barrier. System of barriers ensures safe operations throughout the entire lifecycle of the well and beyond, from initial design to abandonment. Well life cycle consists of three major stages, Figure 13. The first stage is the construction of the well (including drilling, completion, and commissioning to production) (Energy HQ, 2021). Second stage of the well life is production, this period can last 20-30 years, depending on well condition and level of the production (if it is still commercially feasible to exploit the well). The third and the last stage of the well lifecycle is Plug and Abandonment, which lasts forever (The National Petroleum Council, 2021).

Well Integrity is most commonly defined as an "application of technical, operational and organizational solutions to reduce the risk of uncontrolled release of formation fluids throughout the life cycle of a well" (NORSOK standard, 2004). Well integrity management is becoming a vital element in managing corporate risks for operators. Leaks caused by loss of integrity can harm people, the environment, and a company's reputation (Normann, 2019). Nowadays, well integrity is a growing concern due to increased environmental regulations, increased complexity of new wells, development of unconventional resources, and more strict monitoring systems.

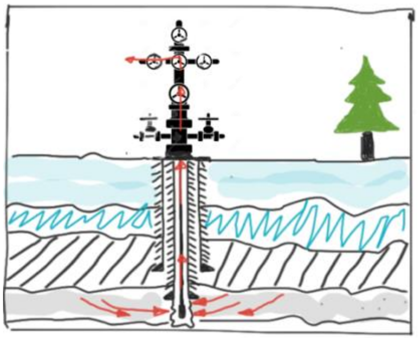
1-5 months (depending on the complexity)



Drilling, well construction and completion

This stage is relatively short, usually from one to three months for onshore, conventional oil wells in Russia (based on the Author experience). This stage in the life of a well is critical since a proper and reliable sealing system can be constructed at this stage. It is important to note, that on all next life well stages, well integrity can only be restored and only on this stage the integrity can be build.

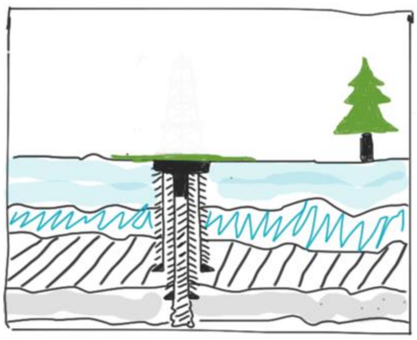
20 years (on average)



Production

The well's longest life stage can last up to 20-30 years, depending on production rate and well condition. During this stage, the well structure can be affected by pressure, temperatures, mechanical and shock loads, and corrosion. Non-integrities and methane emissions mostly developed during this stage. At this stage, a well's purpose can be changed (Producing well can converted to the injecting). Production intensifications methods are utilized (wellbore chemical treatments, hydrofracturing, and others) at this stage.

Infinity



Plugging and abandonment (P &A)

The last stage of the well's life lasts for the unknown time period. Once the well has run out or the production rate is lower than the operating cost, the well needs to be repaired if needed and properly sealed so there are no further methane leaks.

Figure 13 Importance of proper well barriers (integrity) at well life phases

To ensure well integrity in new wells, the cost of well construction may increase due to the better materials selection (i.e., higher casing grade) and longer cementing time (longer rig time rent). To fix the wellbore leak, when non-integrity has already been developed, extra services and additional costs are required. First, the leak must be located downhole, and the exact point of seeping gas should be identified. Then, the leak must be assessed if it is technically possible and financially feasible to repair. Last, the leak is repaired. During the above mentioned operations, the well is shut off and production temperately stopped.

Well Integrity can be achieved for new wells, following industrial standards, such as American petroleum Institute (API) or International Organization for Standardization ISO. For mature wells or wells with already developed methane leaks, the only way to restore integrity is remedial measures (Figure 14).

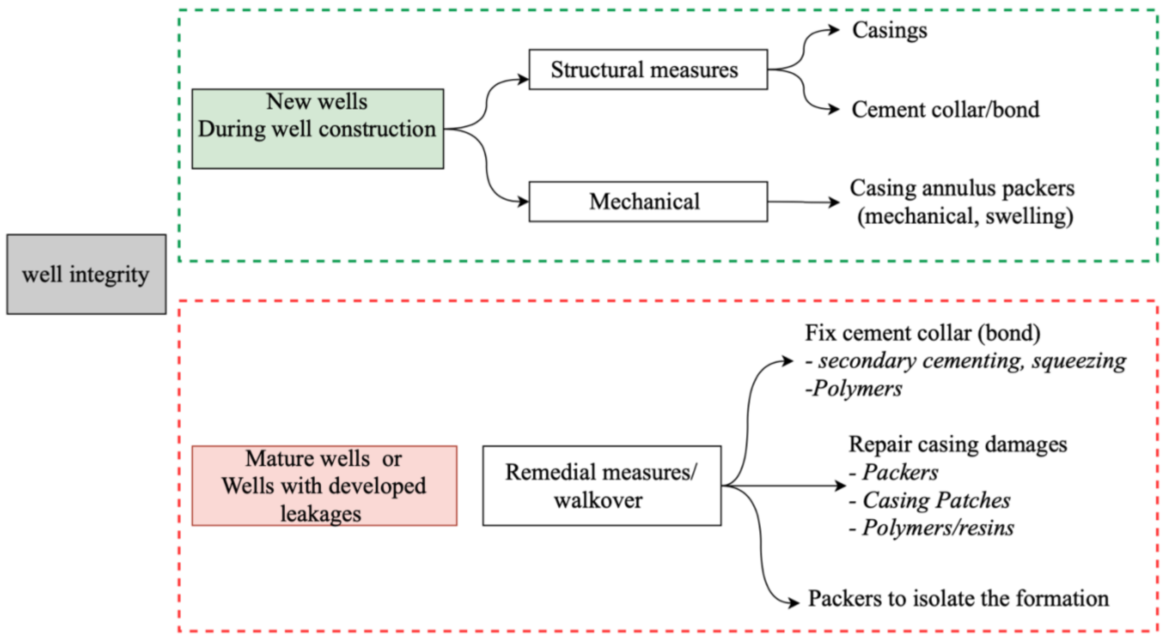


Figure 14 Well integrity for newly constructed wells and for wells with issues

Section 6.2. Well integrity failure

Failure of wellbore integrity leads to negative financial consequences and potentially significant environmental impacts, such as groundwater contamination, gas leakage to the atmosphere, and fluid spills and seepage at the surface (Kiran, et al., 2017). The most famous case of well integrity failure is the British Petroleum (BP) oil spill in the Gulf of Mexico in 2010. According to BP's September 2010 report, the accident started with a well integrity failure (The Guardian, 2021). Integrity failure may develop during the initial drilling, completion, and before commissioning or shortly after the production has started.

Well integrity is not a parameter an operator can measure like temperature or pressure. It is a condition of the well or the condition of the constructed barriers. It is challenging to detect if the well already started developing integrity issues. The earlier an operator is aware of possible integrity issues, the better.

Sustained casing pressure (SCP) is a first indicator of integrity issue, evidence of failure in one of the well barrier elements (Wellcem, 2019). SCP is caused by gas migration from a formation through the leaking cement bond in one of the well's casing annuli. It may also be caused by defect and leaking tubing connections, downhole accessories, or wellhead seals (Pegasus Vertex, Inc. (PVI), 2021). Figure 15 demonstrates the typical formation process of SCP in the well.

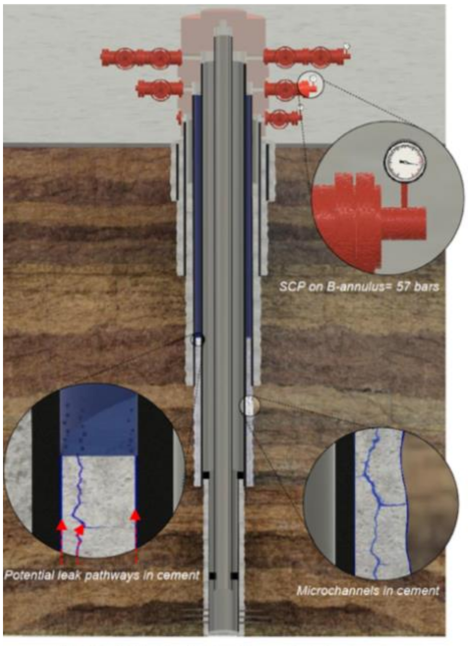


Figure 15 SCP- Sustained casing pressure
Source: (Wellcem, 2021)

Typically, accumulated gas in the casing strings is vented out from the well at a small constant rate. The SCVF is controlled by a valve situated on the wellhead, which may be opened to allow gas to vent to the atmosphere or closed to prevent venting.

There are several possible scenarios after sustained casing pressure buildup. In many cases exploration of the well is safe to continue, depending on how fast the SCP will be rebuilt after venting (Wellcem, 2021). However, wells with detected SCP shall be monitored regularly (every second year for example) and registered. Some wells experience high rates of SCP and high volumes of vented methane, in such cases immediate shutting down and remedial measures are recommended. Figure 16 demonstrates the extreme path of integrity failure development, ultimately leading to the loss of the well.

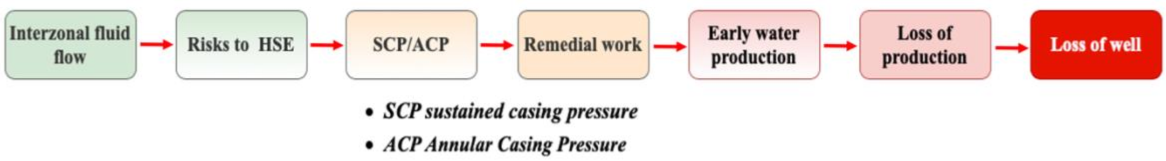


Figure 16 Stages of zonal isolation failure

Section 6.3. Well construction process overview

Oil or gas wells rely on multiple layers of steel and cement barriers to prevent bore hole collapsing and reservoir fluid flow between formations and wellbore. Well construction starts with the drilling of a hole in the earth to the required depth and trajectory. Once a section of a well has been drilled, a steel pipe or casing (Appendix 2) is run from the surface to the bottom. Figure 17 demonstrates the typical design of the well, where steel pipes run into each other, from the bigger size, for example 20" to 7" or smaller.

Figure 17. Several sections of casings in a well
Source: (Canadian Society for Unconventional Resources (CSUR), 2020)

Next, a cement slurry pumps down to the bottom through the casing and then up around the area between the casing pipe and drilled hole -annulus (Appendix 2) forming a robust concrete bond to strengthen the borehole. Well cementing was developed back in 1921 Erle P. Halliburton helping to bring greater production and environmental safety to America's oilfields (The American Oil & Gas Historical Society (AOGHS), 2021). The cement slurry commonly is a mix of Portland cement, water and assorted dry and liquid additives that must harden (typically for 12 to 24 hours) before drilling can be resumed (Appendix 2). Within the timeframe cement achieves similar strength and leak resistance to the rocks through which the hole was drilled. Good quality cementing will likely protect wells against cement degradation and casing corrosion through the well's lifecycle and beyond, Figure 18.

Figure 18 Demonstration of the several sections of cemented casings in the well
Source: (Virginia Department of Mines, Minerals, and Energy, 2021)

Obtaining a proper cement bond is the most critical step in well construction. The following measures can be taken to improve the quality of cementing operations: cleaning of the open hole's surface (using casing scrapers); good casing centralization, and casing rotation and reciprocation during cementing. The drilling fluid (i.e., air, foam, or aqueous-based or oil-based fluid) must be properly selected based on geological and wellbore conditions. The cement slurry must be properly designed (chemical composition and additives) to ensure adequate cement placement (Schlumberger, 2021). There are many important parameters to meet to build an adequately isolated well. Below, in Table 3, the most critical are listed.

Table 3 Critical parameters for successful cementing

Parameter	**Comments**
Cleaning of the well open hole surface	Cleanig from debris, oil, drilling mud and other contaminations to ensure proper bond between cement slurry and open hole surface
Selection of cement slurry	Slurry density. Should be the same as Drilling mud to minimize the risk or blowouts or lost circulation. Cement Strength. Cement in oil wells is subjected to static and dynamic stresses.
Centralization	Casing centralizer is a mechanical device installed on the casing to keep the casing from contacting the wellbore walls and to ensure equal thickness of cement bond.
Cement losses during cementing	Cement losses into fractures of the formation may have certain effect on the height of the cement built in the annulus after pumping a pre-defined volume of cement slurry

Testing of cemented casing strings for integrity is carried out by pressure testing them with liquid, gas and lowering the liquid level. The casing pressure should be at least 10% higher than expected operational pressure. The pressure test's minimum values are regulated and depend on the diameter of the casing. To prevent cracking of the cement collar during testing, the increase in pressure should be less than the critical one, at which the destruction of the cement ring may occur (Dolgih, 2007).

Acoustic sonic and ultrasonic cement evaluation tools can measure the bond between the casing and the cement placed in the wellbore annulus between the casing and wellbore to ensure its equal (Schlumberger, 2020). Confirming the isolation between reservoir layers and wellbore is essential to avoid potential problems, such as crossflow behind the casing between zones. The early detection of poor quality or the absence of cement behind casing is recommended to avoid potential production problems and their associated costs.

Section 6.4. Forms of methane leaks caused but failed integrity.

Wellbore leakages can occur in an actively producing well or a well that has been permanently abandoned after its productive life is over. The possible consequences of wellbore methane leakages are contamination of aquifers and surface waters and contribution to GHG emissions (Wisen, et al.). Methane emissions in the leaky well can be in the shape of surface casing vent flow (SCVF); when methane from formation seeps into the wellbore next to the casing pipe and accumulates there, causing the growth of accumulated casing pressure (ACP) (Appendix 2). Accumulated gas in the annulus then deliberately vents to the atmosphere via a valve on the wellhead. If the casing pressure rebuilds after gas venting, then it is becoming sustained casing pressure (SCP). SCP is defined as any measurable casing pressure that rebuilds after being bled down (Rocha-Valadez, Hasan, Mannan, & Kabir, 2014).

The second form of methane emissions is gas migration (GM). If the well's barrier system fails, it may result in subsurface leakage of methane outside the well; a process termed the fugitive GM (E.Sandla, A.G.Cahillb, L.Welchc, & R.Beckiea, 2021). Figure 19 indicates in red a possible GM paths. Paths to the surface can vary significantly due to geological structure. Natural gas can channel its way between formation layers and then runs into a cased or open hole in the oil well and finally escapes to the surface.

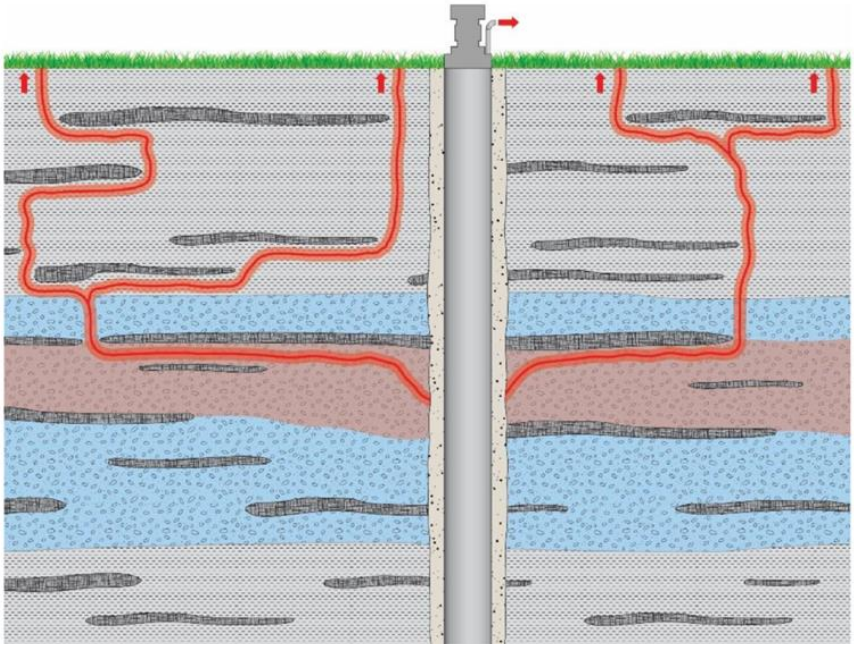


Figure 19 Methane emissions to the atmosphere (possible paths)
(Neil A. Fleming, 2019)

Section 6.5. Most common reasons of well integrity failures

Integrity breach can happen in the short-term after well commissioning. In this case, non-integrities are not time-related and mostly occur due to poor quality of well construction or mistakes in well design . Examples of such non-integrities could be: The complex trajectory of a well, with a sharp angle; Poor cementing quality (gas bubbles in the slurry, unequal cement bond, poor centralization, etc.); Improper selection of casing pipes (burst/collapse, corrosion); Leaking casing pipe threads if connected incorrectly; the casing connection is presented in Figure 20.

Figure 20 Casing pipe connection
Source: (Weatherford, 2021)

Non-integrities, which occur a long time after the production started, are time-dependent, meaning that some time is required for well barriers to fail and non-integrity to appear. Even if the well was adequately sealed (appropriate barriers built) during construction, a leakage problem might develop due to casing pipe corrosion or cement shrinkage; visual examples are presented in Figure 21. Operational and mechanical stress such as high temperature difference, pressure difference and aggressive well environment (H2S, CO2 presence, high temperature, high pressure) are the most common reasons for time-dependent integrity failures.

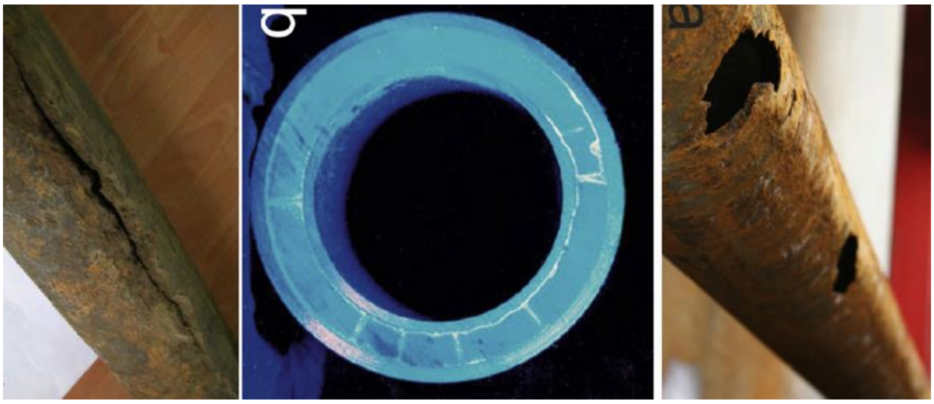


Figure 21 Time related non-integrities examples
(Davies, Almond, Ward, & Jackson, 2014)

Tubing is the pipe transports the oil and gas from deep in the well to the surface (Voestalpine, 2021). Tubing damages is the most common reason for integrity failure with 39% (MiReCOL, 2015)); a possible explanation is corrosion. The second most common reasons for integrity failures listed are casing and cement non-integrities, with 11% each. Table 4 lists most common causes of integrity failures. Downhole Safety Valves (DHSV) (Appendix 2) refer to a downhole device that isolates wellbore pressure and fluids in an emergency or catastrophic failure of surface equipment.

Table 4 Explanations of well integrity failures

Casing	**Cement**	**DHSV**	**Packer**	**Tubing**	**Wellhead**
11 % of failures	11 % of failures	3 % of failures	5 % of failures	39 % of failures	5 % of failures

Source: (MiReCOL, 2015)

Integrity failures present environmental and safety risks because methane or other previously injected fluids may flow to the surface or into nearby aquifers. It is not only sufficient to achieve good zonal isolation at the well construction stage but to also ensure that the seal lasts many years during the well operations and beyond the well's life.

Chapter 7. Integrity remedial measures

The Integrity remediation process consists of the following steps: first identifying and assessing the size of the leak, next locating the leak point, and finally repairing the leak and verifying the seal. This chapter discusses the existing technologies of wells remediation their advantages and limitations. Currently, numerous emerging technologies are becoming available due to increased demand for integrity remediation services. Focus on well integrity measures increased when exploration and production companies started looking for cost-effective ways to improve the existing fields' recovery. Wells that were shut off due to the well integrity issues became obvious opportunities for production gain. These issues also drew attention to the need for better processes and systems to improve well integrity performance (Kumar, 2021).

Wellbore leaks appear due to developed pathways for unwanted reservoir fluid, including gas to get to the wellbore. All leaks are located below the rotary table or downhole. Several leak types could be in one well simultaneously, for example, cracks in the cement bond and corrosion-related holes in the casing pipes. Diverse forms of non-integrities require different technologies and materials for remediation.

The casing pipe is the first line of defense against leaks. Second, cement integrity – where cement bond is analyzed. In the last group, other wellbore components can fail or leak in a variety of ways. Pinpointing the leaks' source can catch small problems before they grow into larger issues that damage the well or decrease productivity.

Section 7.1. Wellbore leakage location

Wellbore leakage location starts with on-surface detection of methane influxes. As mentioned before, there are two major shapes of methane emissions caused by well sealing system failure. First is fugitive gas migration (GM), a geographically dispersed leak, can occur at some distance from the wellbore. Currently, there is a lack of knowledge on the occurrence, distribution, fate, and transport of fugitive gas (Forde, 2019). There is often on surface visual evidence in GM's, such as dead vegetation and bubbling of standing water. The other way of on-surface detection of GM is to use infrared cameras (Opgal, 2021) which make methane leaks visible. However, considering GM's wide geographical disperse, distances between oil wells in Russia, and challenging logistical access, all methods mentioned above are labor-intense and costly.

In the case of vented methane SCVF, the major evidence of downhole leaks is the presence of sustained casing pressure (SCP), which was rebuilt after gas was vented. Most commonly, casinghead gas is vented directly to the atmosphere, either continuously or periodically to relieve pressure build-up to continue oil production (CCAC Oil and Gas Methane Partnership (OGMP), 2015). Monitoring of sustained casing pressure (SCP) is recommended, and the rate of SCVF can be measured. If the rate is considered severe, the well must be remediated immediately as such a condition presents significant risks to the environment and public safety. SCVF classified as non-severe must be monitored annually for five years to ensure the leak does not increase and become severe.

In Russia, national standards regulate safety in oil and gas industry "Safety rules in the oil and gas industry" (Federal Environmental, Industrial and Nuclear Supervision Service, 2020). Part XV of the rules lists the requirements for the oil and gas wells design, including the following. The wellhead design should allow the operator to prevent the seepage of the reservoir's fluids into the annulus, ensure the integrity of well annulus during drilling and exploration, run the pressure tests, and check the annulus integrity. Frequency and means of checking the condition of casing strings as they wear out over time or their emergency destruction (collapse, rupture, or other deformations) should be considered in the field development project and provided by the operator before the start of field development. The field development project should also contain the necessary measures to prevent accidents and repairing technologies. After presence of methane emission is confirmed, the next step is to locate a leak downhole.

The most commonly used technology for downhole leak detection is cement bond logs (CBLs). CBLs is an acoustic device used to detect the presence or absence of a cement bond between casing and formation (Leeth, Cement-bond logs (CBL) estimates of well integrity and zone isolation., 2015). Acoustic signals are emitted by a transmitter installed in a wireline logging tool, which travels through a casing section to evaluate the cement condition. A receiver, installed in the same device below the transmitter, measures the arrival time of the transmitted and reflected acoustic waves. Interpretation of the received data allows the evaluation of the condition of cement bond and identifies breaches such as channeling comprised cement and microcannulas; an example is given in Figure 22. These characteristics help the operator to understand the quality of cement collar and if remedial measures are required.

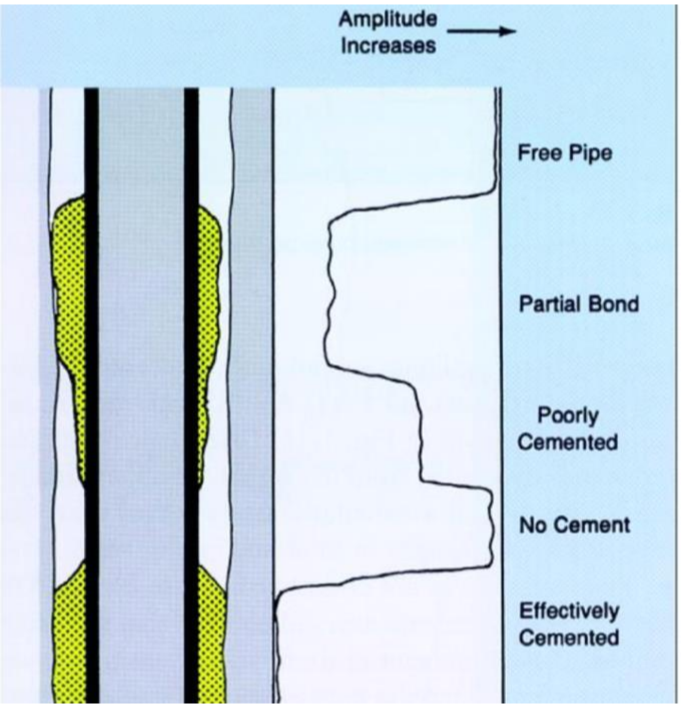


Figure 22 Interpretation of the CBLs results
Source: (Leeth, Properly run and interpreted, cement-bond logs (CBL) provide highly reliable estimates of well integrity and zone isolation, 2015)

The second common technology to locate a leak downhole is spectral noise logging (SNL), which monitors fluid flow behind the casing. (GR Energy Services, 2021). Based on SNL and high-precision temperature (HPT), the combined HPT-SNL tool accurately identifies leaks in the casing pipe or tubing. This leak detection method is a two-stage process. In the first stage, temperature and noise are recorded under shut-in conditions (when a casing head valve is closed, and casing gas accumulates in the annulus). In the second stage, temperature and spectral noise surveys are conducted while bleeding off fluid from the problematic annulus. Excess pressure bleed-off causes extra fluid to enter the annulus, which is detected by the temperature and noise logs. Figure 23 demonstrates the leak detection using SNL.

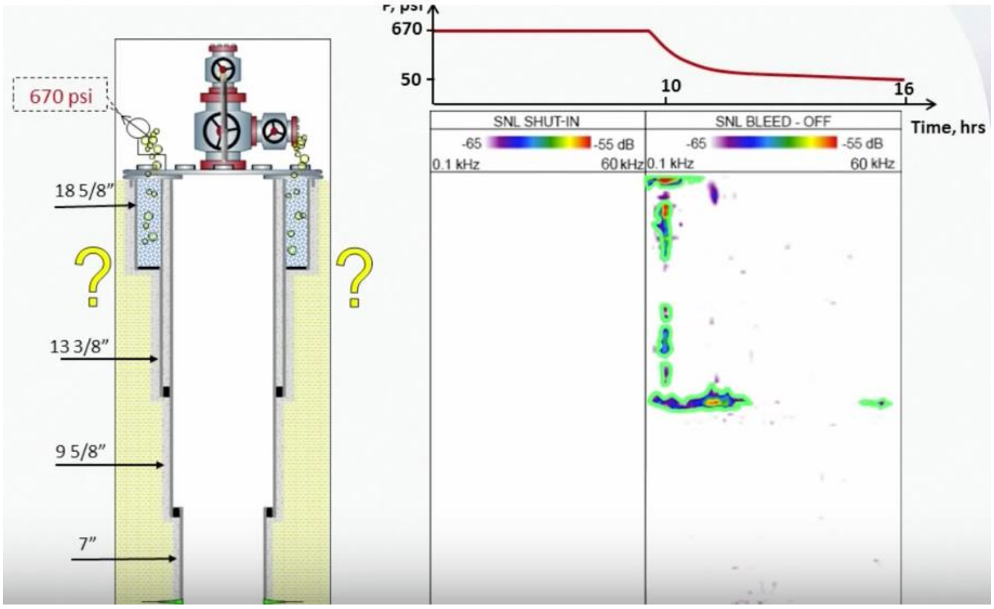


Figure 23 Leak detection with spectral noise logging (SNL)
Source: (TGT Oil&Gas Services, 2021)

The newest solution on the market, targeting leakages monitoring is the Intelligent Pipe solution. Where pipes monitor pressure and temperature of the entire wellbore in real-time, anticipating any abnormal annulus behaviour. Moreover, real-time monitoring can mitigate the risk of annular pressure build-up (APB). Oil producers can benefit from a much quicker reaction time as soon as any abnormal well behaviour is detected. With the Intelligent Pipe solution, operators are immediately alerted about any leakage (Vallourec, 2021). Detecting and measuring methane emissions comprehensively and cost-effectively remains a challenge because of the high service cost. When the cause of the leak has been determined, corrective actions can proceed.

Section 7.2. Overview of integrity remedial methods and technologies

Section 7.2.1. Cement bond remedial measure (secondary) cementing

Secondary cementing (Appendix 2) is cementing operations performed to repair primary-cementing problems or treat non-integrities in cement bonds after the wellbore has been constructed. The two main categories of remedial cementing include squeezing cementing and the placement of cement plugs. Cement is squeezed into the damaged bond to restore isolation without decreasing the wellbore internal diameter (ID). Alternative technology to fix a cement bond is to install a cement plug or mechanical packer placed around the damaged zone.

About 15% of primary cement jobs require squeezing (Semantic Scholar, 2021). Primary cementing cost is estimated as 5% of well cost, versus 17% of the secondary cementing cost (George E. King, 2019). A squeeze operation performs to fill the void space with a sealing material, typically cement, to achieve a suitable seal. However, when one leak pathway may seal, squeezing can create (fracture) cracks.

Other repairing technologies becoming available on the market are pressure-activated sealants and temperature-activated sealants. The pressure-activated sealants react to high differential pressure at the leakage point. Pressure differences cause the polymerization of the sealant into a flexible solid. The reaction stops when the pressure drops, and the resulting sealant fills cracks or holes, without extra pressure applied (different to squeezing). Another advantage of the pressure-activated sealant solution is that there is no need for workover, which means no need to stop the production, which reduces the costs (MiReCOL, 2015). The second sealant alternative is a temperature-activated sealant; they are designed to react at a specific temperature. Reacting at a certain temperature allowing the placement, pumping, or squeezing of sealant in the liquid state to the desired location. Temperature-activated sealants can be used for remediation of casing and annular cement integrity loss (MiReCOL, 2015).

Section 7.2.2. Casing pipes repair technologies

Casing Patch is a permanent solution, repairing damaged tubing zones or casing, shutting off unwanted channels, and shutting off gas and water, restored integrity. An expandable steel patch can be run through tubing across the damaged zone and to fix the leaking casing as shown in Figure 24. Casing Patch consists of high-quality stainless steel and elastomer with a sealing system (Saltel Industries, 2020). The patch expands using a high-pressure inflatable packer at the leak point's depth, pushing it against the casing and over-pressuring to activate the casing patch's outer seals. Casing Patches provide the maximum internal diameter, leaving full access to the well below the patch. Casing Patches can also be used for damaged tubular, slotted liners, or screens in thermal applications.

Figure 24 Casing Patch (against corroded area or pipe)
Source: (Saltel Industries, 2020)

Each remedial integrity job is unique and should be treated as such. There is no universal sealing material, and sealant must be designed to meet the wellbore conditions and the size of non-integrity. Remedial efforts are often quite unsatisfactory. Success rates of less than 50% are frequently reported, with on average, three interventions required to stop the gas migration successfully (Dusseault, Jackson, & Macdonald, 2014). Some companies report a success rate of remedial operations at over 80% (Reference: Information acquired from the Author personal experience). However, it is common to assess the problem before agreeing to start the remedial operations; thus, the severe cases with low success chances are not taken.

Chapter 8. Analysis of oil wells inventory in Russia

An oil wells Inventory is a key input needed for estimation of methane emissions related to integrity failures and their reduction estimations. Well Inventory counts and classify oil wells by purpose and condition (e.g., active, idle). Well Inventory includes all exploration, production, observation, and special wells. Since the study is limited to the oil-producing wells located onshore, only wells assigned to oil production are considered. The following sections describe quantity and the condition of the oil wells in Russia.

Section 8.1. Total number oil production assigned wells in Russia

The total number of wells is subdivided into wells currently in operation (or active) and the idle wells, which are undergoing capital repairs or awaiting capital repairs. Active wells include wells, which were in operation in the last month of the reporting period, regardless of the number of days of their operation in that month (Ministry of Oil Industry of the USSR, 2021). By the end of 2019, the total number of oil wells grew by 2.9 thousand wells (+1.6% compared to 2018) and amounted to 180.4 thousand wells, Figure 25. Most noticeable growth occurred in the European part of Russia and Western Siberia. Simultaneously, the number of active oil wells in Russia decreased in 2019 compared 2018 and reached 155.0 thousand oil wells. As a result, the average share of active wells out of the total number decreased over the year from 87.4% to 85.9% (Ministry of Energy of the Russian Federation, 2020). The number of the wells completed in 2017 will be used, 175 thousand wells, since, the latest available methane emissions data as of 2017, Section 3.5.3.

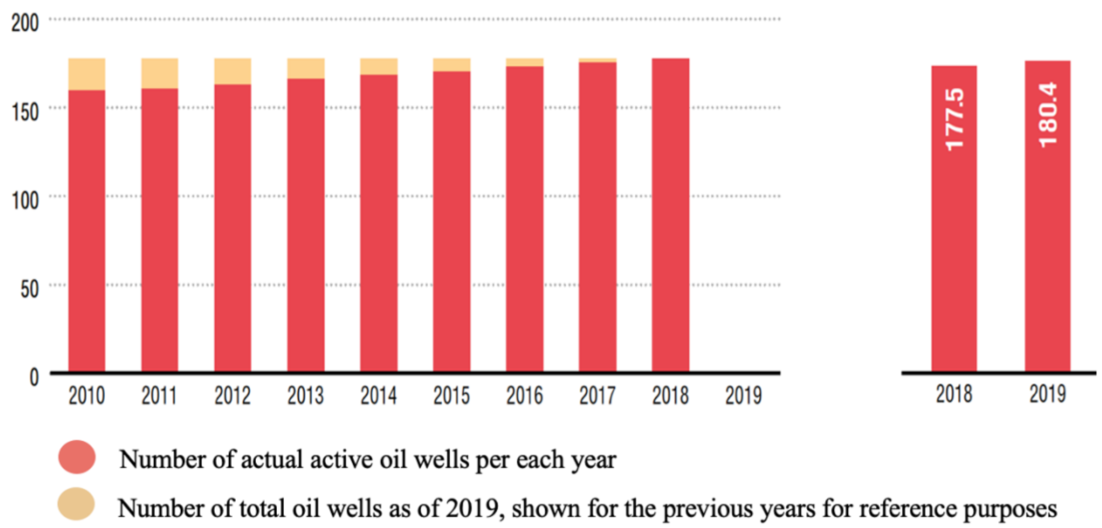


Figure 25 Total number of the oil wells in Russia (thousand wells)
Source: (Ministry of Energy of the Russian Federation, 2020)

Idle or inactive well can be repaired to continue production or should be liquidated (plugged and abandoned (P&A)). Plug and abandonment can be both temporary and permanent. The permanent one is typically performed when the well is no longer commercially feasible (FloPetrol well Barrier, 2021). In Russia, well liquidation processes are strictly regulated. The field operator must restore integrity of each well before liquidation to prevent downhole leakages and related methane emissions to the atmosphere. The biggest oil producer in Russia is PJSC Rosneft Oil Company with 35% of total oil production in the country in 2019 (Ministry of Energy of the Russian Federation, 2020). PJSC Rosneft is a national oil company (NOC), with more than 50% National ownership. Therefore, there should be no or insignificant risk of the national oil-producing company becoming bankrupt and not carrying out wells' repair expenses before abandonment. Yet, there is no guaranty that the company would prioritize long-term environmental goals over short-term high marginal goals, such as measures to increase the production or investing into new fields development.

In Russia, around 2000-7000 wells are idle for a couple of decades and not liquidated (estimation is based on Rosimushchestvo expert opinion). During the privatization process in the 1990s, those wells were damaged or had little production rate, and no company wanted to take them on the balances. Currently, mentioned wells are on the Federal Agency for State Property Management (Rosimushchestvo) balance, but substantial investments are required to repair wells and P&A after.

Section 8.2. New completed and commissioned wells

Shortly after new well constructed and exploration has started, the first non-integrities can occur. Such non-integrities are caused by improper well design, poor cementing job, wrong selection of materials, wrong well trajectory, and other design and operational mistakes. If such mistakes at the well construction stage can be minimized or avoided, wellbore leaks and methane emissions can be prevented or delayed, and the life expectancy of the well extended. In 2019 a total of 7,850 oil wells were drilled, completed, and commissioned (Figure 26).

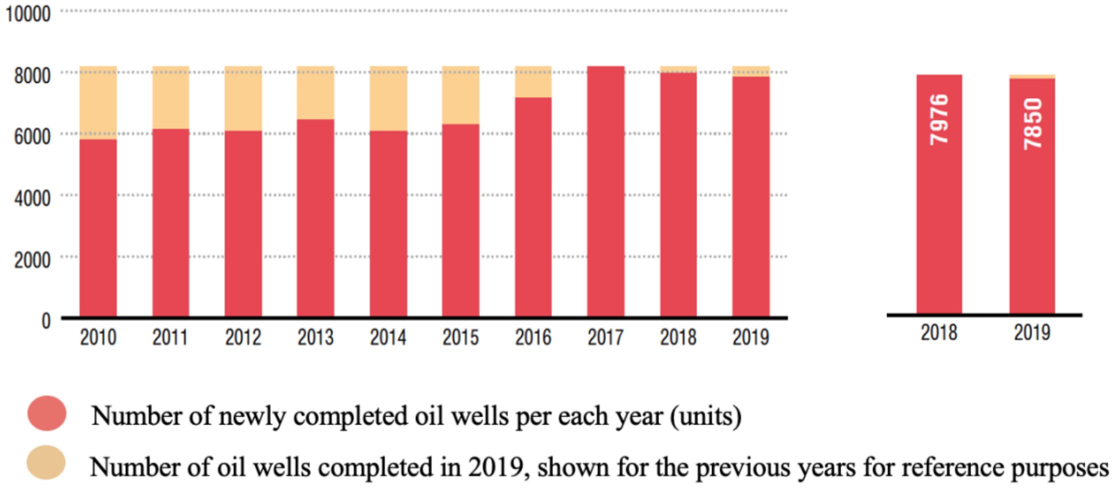


Figure 26 Number of newly completed oil wells a year (pcs) and average well depth (m)
Source: (Ministry of Energy of the Russian Federation, 2020)

Section 8.3. Factors potentially affecting well integrity

Although it is recommended to regularly check all wells to detect methane emissions and possible integrity issues, it is impossible to always execute due to high costs, logistical and seasonable limitations, particularly in Russia's case. Integrity failure, is impossible to forecast or model without real-time well data collection, such as pressure, temperature. Today's well integrity management approach is still reactive, not proactive targeting prevention of well integrity issues before they occur.

Baker Hughes Company offers a solution - BHC3™ for real-time integrity monitoring. This solution provides real-time well monitoring and predicts formation and mechanical issues before integrity issues occur. BHC3 aggregates well data, such as annulus pressure, temperature, flow rate, water cut, gas fraction, and uses machine learning to identify potential causes of failure. Proactive understanding of the well health (integrity) allows field operators to prioritize wells that require intervention and understand the potential economic, safety and environmental impact of an incident (Baker Hughes, 2021).

However, this solution cannot be used for every existing well due to the high costs and possible technical constraints (downhole data acquisition infrastructure). Reducing the number of wells to the ones with the highest integrity risk could be a solution well integrity management. Several parameters could be listed to identify the wells with the highest potential risks or integrity failures.

Table 5 presents parameters most likely to affect well integrity. The list is based on personal experience and industry experts' interviews. These parameters help define wells with high risks of non-integrities. Out of the total well number, producing companies can target the group of wells with higher risks of non-integrities, which shall be checked to ensure integrity.

Table 5 Factors which increase risks of well integrity failures

Parameter	Comments	Suggested value when consider well at higher risk
Age of the well	The older the well, mostly the higher the chances of integrity issues	>15 years
Well design	Particularly well trajectory (sharp angles, horizontal, slant well, complex trajectory), may increase chances of poor cementing job	Horizontal and slant wells
Type of well completion	Wells with open hole type of completion lead to the higher chances of integrity problems	Open hole completion
Type of primarily artificial lift	Gas-lift is an artificial lift method in which gas is injected into the production tubing to reduce the hydrostatic pressure of the fluid column.	Gas lift
Presence of aggressive substances in the well environment	H2S, CO2, bacterial corrosion presence, in combination with high bottomhole temperature and pressure	Presence of min two parameters in the well environment (High pressure, high temperature+ CO2, H2S)
Gas/oil ratio (GOR) or water/oil ratio (WOR)- The ratio of produced gas or water to produced oil	Abrupt change of gas/oil ratio (GOR) or water/oil ratio (WOR) can indicate well integrity issues	Monitor changes in GOR and WOR

One of the listed factor is well design or trajectory. Reflecting the general state of gradual deterioration of conventional oil reserves, the average depth of newly commissioned oil-producing wells increased from 3,081 m to 3,103 m (2019 vs 2018). Producing companies aim to increase efficiency and oil output from each well, including drilling fewer wells, but longer and with a horizontal trajectory of the production string. Consequently, the rate of horizontal drilling improved as shown in Figure 27.

In total, the volume of horizontal drilling in Russia in 2019 increased to 144,425 meters from 133,384 meters, adding +7.8% to the 2018 level (Ministry of Energy of the Russian Federation, 2020).

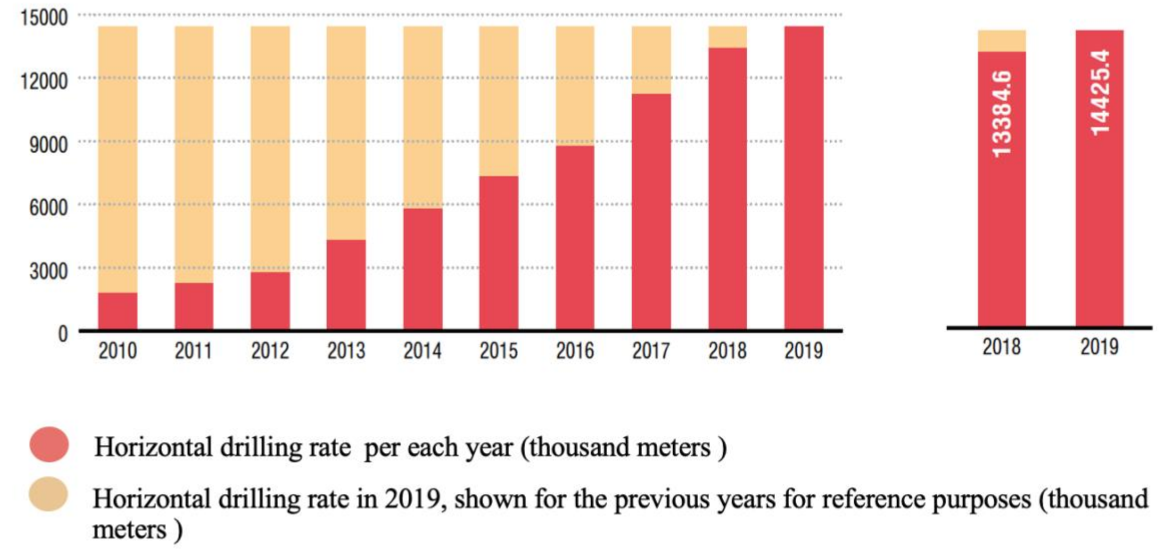


Figure 27 Horizontal drilling trends in Russia (thousand meters)
Source: (Ministry of Energy of the Russian Federation, 2020)

In the David Hardie study (David Hardie, 2015) the connection of well deviation and integrity failures rate is discussed. Figure 28, presents that leak rates increased with the increased well deviation, from 3.7% for vertical wells to 5.6% for horizontal wells, deeper than 600 m.

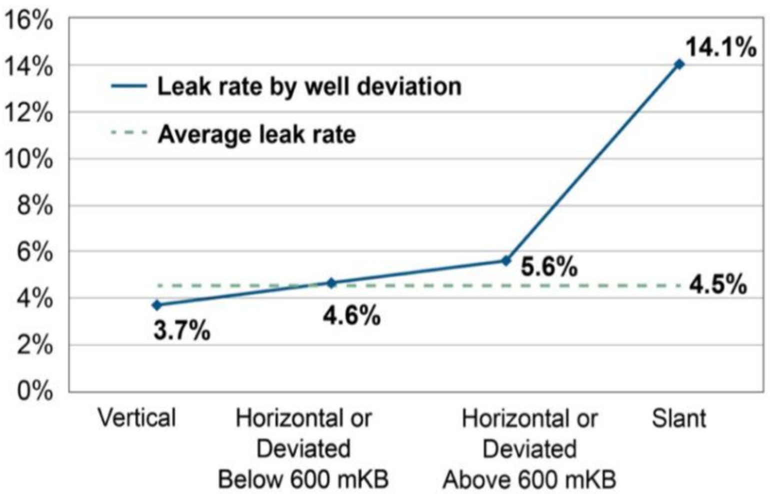


Figure 28 Influence of deviation on well integrity (both active and inactive wells)
Source: (David Hardie, 2015)[1]

For slant well trajectory leaks rate reaching 14.1%. Slant drilling differs from directional drilling in that the drill angle starts at the surface and not from a vertical wellbore, as presented in Figure 29.

[1] mKB – the same as true vertical depth (TVD), distance between Kelly Bushing and survey point.

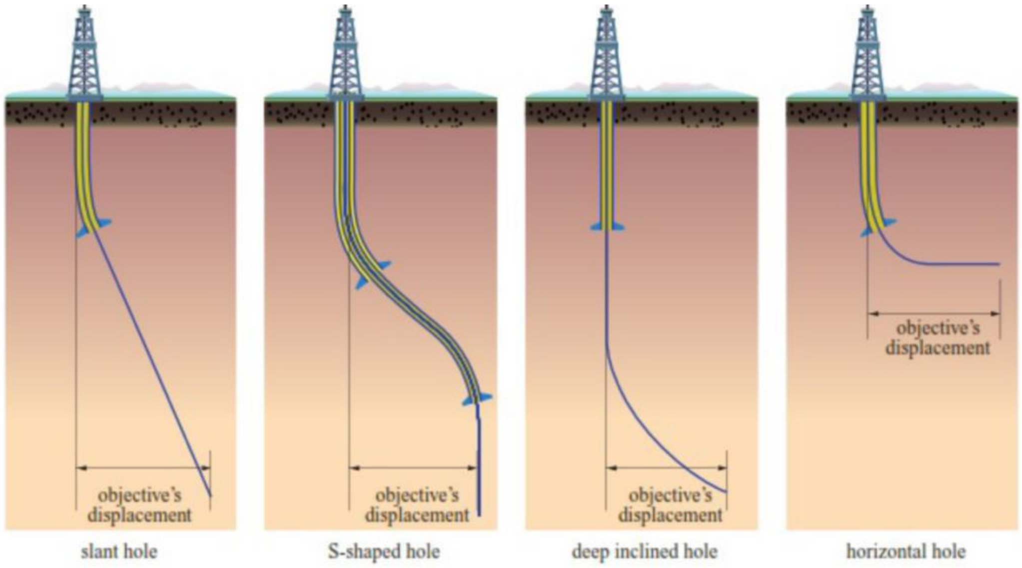


Figure 29 Types of well trajectories
Source: (Valiant energy services, 2021)

Parameters mentioned in table 5 can be very useful for the producing companies to narrow the search area to ensure that only wells in the high-risk group are the subjects for an integrity monitoring. The oil-producing company has comprehensive information about wells, which are on their balance. However, this information is not publicly available, thus cannot be used for the study purpose, particularly for estimating the well's share with integrity issues. It would be useful to conduct independent research with the single goal to identify parameters affecting the integrity, to create a detailed matrix with parameters, and pinpoint the wells with the highest risks of non-integrities developments. Also, making a parameters matrix would allow estimating more accurate methane emissions caused by non- integrities.

Chapter 9. Regulations, and practices of well integrity monitoring

When a well barriers system fails, the gas channels its way up to the surface and can take the form of surface casing vent flow (SCVF) or gas migration (GM). Oil-producing companies can monitor well integrity to prevent severe methane leaks and timely repair the well or shut down it for plugging and abandonment. However, integrity is not a parameter you can measure, such as temperature or pressure, but more a condition of the well barriers. When a barrier system fails, well integrity is compromised. A parameter, which can be monitored is sustained casing pressure (SCP) (SPE Drilliling and completion , 2014). SCP is defined as any measurable casing pressure that rebuilds after being bled down.

Emerging technologies enable field operators to monitor SCP continuously and remotely. For example, the HiberHilo solution (Hiber, 2021) provides a solution with satellites, where the data are sent straight to the operator dashboard. HiberHilo satellite network gives global coverage, so even the most remote locations can be monitored. Each pressure monitor sensor has a battery (2-3 years battery life length) and is equipped with a solar panel for power (Hiber, 2021). However, the solution's significant downside is the temperature limitation; now, the solution is suitable for conditions not colder than 20 degrees Celsius. In Russia in western and eastern Siberia, winter temperature can go as low as minus 50 degrees Celsius and even below. To summarize, there are three parameters indicating the presence of well integrity issues. The main one is SCP (sustained casing pressure) when gas is accumulated in the casing annulus; gas ventilated via a casing head valve forms SCVF, Figure 30. Consider a situation where the valve is closed and causing gas to continue to build up. In that case, this could result not only in the safety risks but also gas can migrate through channels in formations and result in GM or contaminated aquifers. Vented casing gas SCVF can be measured, and results can be recorded and reported, yet it is not a common practice.

In some cases, the surface casing valve is permanently open to prevent any safety risks and casing gas ventilated to the atmosphere. GM is another form of surface gas due to well integrity failures. GM is difficult to measure, detect and monitor due to the geospatial diffusion and unpredicted location.

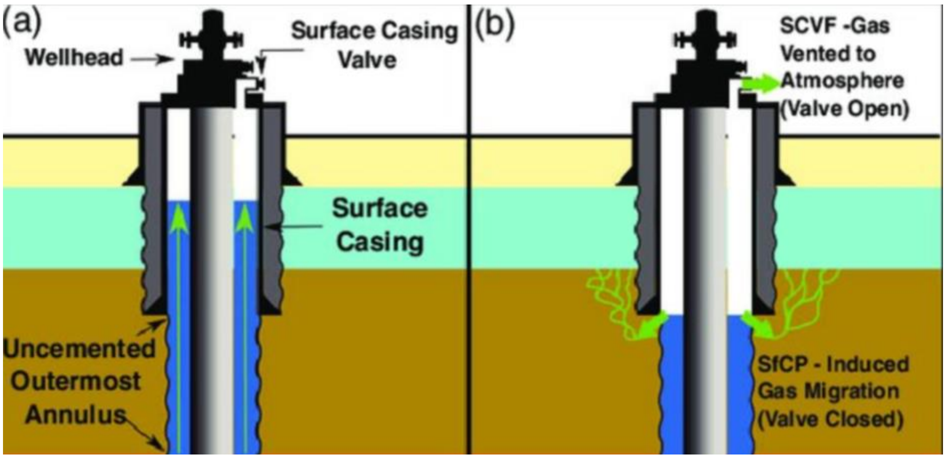


Figure 30 a- sustained casing pressure (SCP); b- surface casing vent (SCVF); gas migration (GM)
Source: (Rice, Lackey, Proctor, & Singha, 2018)

Countries have different regulations and practices to measure sustained gas pressure (SCP) and on surface methane emissions in SCVF or GM. The next section reviews oil wells monitoring regulations in different countries. GM detection and monitoring is a technically challenging task due to the emission geospatial dispersion. Manual detection and monitoring are possible with infrared cameras, but it could be costly, labor-intensive, and an additional challenges in Russia is logistical access, seasonalable limitations and distances.

Section 9.1. SCVF and GM monitoring regulations and practices in different countries

Most jurisdictions allow some methane leakage during a well's lifetime but require integrity restoration before plugging and abandonment (P&A) (Natural Resources Canada, 2019). Regulations monitoring and detection of SCVF or GM differ from country to country. The following chapter summaries methane emissions regulations on the national and regional levels in Canada, Norway, and Russia, results in Table 6.

Throughout Canada, wells must be monitored for SCVF and GM after they are completed and commissioned. New Brunswick and British Columbia regions require annual monitoring of all wells with detected SCVF and GM (Natural Resources Canada, 2019). The Alberta Energy Regulator (AER) regulates the petroleum industry, including well construction, testing, remediation, and abandonment in Alberta. In July 2020, AER drafted a new directive, "Well Integrity management," where some measures were softened; for example, nonserious surface casing vent flows (SCVF) would be tested in years one, two, and six instead of every year for five years (Alberta Energy Regulator, 2020). GM testing is required only in areas where GM is expected or where the impact on vegetation, groundwater, or safety is obvious and can be visually detected. A surface casing vent test (SCVT) consists of a bubble test; flow rate and pressure measurements if the bubble test is positive. Emissions are reported in cubic meters per day and extrapolated to provide daily rates and annual emission volumes. Monitoring of GM and estimating emission rates is more complicated than SCVF because the flow is dispersed geographically. Soil gas probes or other similar instruments are used to detect the presence of natural gas. The results are reported in parts per million or as a percentage of the lower explosive limit of methane within a sample (Natural Resources Canada, 2019).

In Norway, the field licensees are responsible for controlling the operator to comply with the regulations. The operator shall establish, follow up and further develop a management system to ensure compliance with well-integrity requirements. The operator should also see that all involved parties and contractors carrying out the activities have their management system to ensure well integrity (NORSOK standard, 2004).

Section 9.2. Analysis of industrial regulations in Russia

A well is an object of potential increased danger. Thus, all wells' processes are strictly regulated by Rostechnadzor - Federal Environmental, Industrial, and Nuclear Supervision Service. Rostechnadzor is a federal executive body exercising functions of elaborating and implementing state policy and regulatory, legal control in industrial and nuclear supervision (Federal Environmental, Industrial and Nuclear Supervision Service, 2021).

A completed well is transferred from the service contractor to the customer, field operator or license holder under the Transfer Act. This Act is prepared by a commission (including representatives of the oil field operator and drilling company). A transfer act should contain the following information: basic information about the well (well number, area, depth of productive formations, etc.); well profile and trajectory; production casing integrity test result (pressure test); information on any performed repair work and characteristics of the equipment run into the well and installed at the wellhead (Federal Environmental, Industrial and Nuclear Supervision Service, 2020).

Together with the Transfer Act, the customer receives the well passport (or package of required documents). A well passport contains the following documents: drilling project, cementing acts, integrity tests results for each casing string, and more. Completed wells are commissioned only after a positive conclusion of the local authorities of the Rostechnadzor. Changing the well status, such as temporary conservation or plug and abandonment, is also regulated, a special commission is needed, and the local Rostechnadzor entity's approval is required.

Federal regulations in the field of industrial safety regulate well design and require an optimal number of casing pipes and selection of casing pipes, considering maximum expected external and internal pressures, loads arising as a result of spatial curvature of the wellbore (Federal Environmental, Industrial and Nuclear Supervision Service, 2020). The design of the wellhead casing heads should enable integrity testing of casing pipes and annular spaces.

Oil well passport (a document, which contains all information about the well) must include methods for assessing the casing strings and frequency of the casing integrity testing. To my knowledge, there are no national regulations or requirements on frequency and methods of integrity testing (Federal Environmental, Industrial and Nuclear Supervision Service, 2020).

Table 6 Integrity monitoring practices in different countries

Country	County region	After well constructed	During production	Plug and abandonment	Regulating body
Canada	Alberta	Throughout Canada, wells must be monitored for SCVF and GM after they are drilled	SCVF- Nonserious surface casing vent flows would be tested in years one, two, and six instead of every year for five years	Before abandonment integrity in all wells must be restored	Alberta Energy Regulator
			GM monitoring is required only in areas where GM is common or where the impacts on vegetation		
	British Columbia		British Columbia and New Brunswick regions require annual monitoring of all wells with SCVF and GM		
	New Brunswick				
Norway		The operator shall establish, follow up and further develop a management system in order to ensure compliance with well-integrity requirements			
Russia		After well completed, integrity tests must be passed, before well will be commissioned and further exploitation is allowed	Well project/passport must include methods for assessing the condition of casing strings, methods and frequency of the casing testing (for integrity). That is the responsibility of field operator (producing company)	Before abandonment integrity in all wells must be restored	ROSTECHNASZOR (regional entity)

(GM) Gas migration; (SCP) surface casing pressure; SCVF

Chapter 10. Reduction potential of wellbore methane emissions in Russia

This study's main objective is to assess the potential reduction in emissions caused by the destruction of wellbore barriers or loss of well integrity. The logic for estimating the reduction is shown in Figure 2 Chapter 2. Some parameters are available, while others need to be estimated. First, it is necessary to estimate the proportion of oil wells with integrity problems in Russia. As mentioned before, no data is openly available on the number of wells with integrity issues in Russia or how many wells display SCVF or the presence of sustained casing pressure (SCP). Integrity cannot be measured like temperature or pressure, and oil-producing companies do not report integrity as a separate parameter. Despite the differences such as geology and climate, well-design and well-construction principles are similar for all locations and countries. To improve on the general lack of information on well integrity issues in Russia, a survey was conducted among oil industry experts to identify factors such as share of wells with integrity issues and the average cost of repair. Next Section 10.1 describes the survey aim, questions, sample group and results.

Section 10.1. Survey description

The survey's main purpose is to collect opinions or assessments on various well integrity aspects from participants who work in the industry. As discussed above, there is little information available on methane emissions associated with well integrity in Russia. The survey results should help identify information that is lacking to assess the potential methane emissions reductions associated with well integrity issues and determine the costs involved. The survey consists of seven questions, Table 7. In most of the questions, participants should select from the suggested variants of the answer. The next few sections will discuss each question of the survey and its results.

Table 7 Survey questions

#	Survey question	Comments
1	What is your best educated guess of the share (%) of wells with integrity issues in Russia (onshore conventional oil wells)	Information is required to assess the number of the wells with integrity issues in Russia
2	In your opinion what is the most efficient (cost/labor intensive and safe) way of SCVF (surface casing vent flow) detection and monitoring	Information is needed to suggest the actions aiming methane emissions reductions
3	In how many cases well integrity can be restored (%)?	Information is required to assess the emissions reduction potential (share of wells, where non integrities can be repaired)
4	Based on your experience how much would you assess the cost of integrity repair for one well (onshore, conventional oil)	Information is required to estimate the cost of wells repair
5	After the well has been restored, how long do you expect the integrity to last?	Information is required to estimate the cost of wells repair
6	In your opinion, what is most important for SCVF (Surface Casing Vent Flow) mitigation?	Necessary to understand the obstacles and barriers, preventing oil- producing companies to repair non integrities
7	Please rate the possible barriers of well integrity restoring measures implementation in Russia	Necessary to understand the obstacles and barriers, preventing oil- producing companies to repair non integrities

Survey participants were selected from the industry experts, which the Author knows personally to ensure the willingness to provide answers on the potentially sensitive topic. The group of core participants consists of the people I have met personally throughout my career. On top of the core participants, a survey was sent (via email and LinkedIn) to several industry experts with vast experience in well integrity; however, no feedback was received. Contributors have diverse backgrounds and experience in the industry. However, all of them work in the areas related to the well construction or well completion. Differences between international and local experience can lead to potential biases in the answers as operations practices and excellences differ in Russia from other countries. Half of the participants have mostly engineering experience; they know that it is necessary to build a reliable well with long-lasting integrity, measures such a better well design, casing pipes selections, types of completion. The other half of the participants have extensive field experience; they can assess the operations practices and operational issues firsthand. Table 8 presents the participants experience and background. Two mentioned groups have a different perception of the situation with integrity. For example, five participants with the extensive field experience, all selected an option of 75% of the wells in Russia have integrity issues. At the same time, participants who have mostly engineering experience selected lower share of the wells with non-integrities, 30% and 50%, with average selected share 38%. The possible reason is that field operation may sometimes deviate from the standards and norms. The questionnaire was created with the google forms. And the survey was sent to the participants by electronic mail. A copy of the survey is contained in Appendix 1.

Next sections of the study briefly discuss the results of the survey. Only answers needed for the estimation of methane emissions reduction and required costs were reviewed. Questions related to barriers and further recommendations for emissions reductions in Russia, were assessed in the conclusion.

Table 8 Survey participants description

	Total experience (years)	Geography	Type of experience
Participant 1	>25	Global	Both engineering and field
Participant 2	>10	Russia	Both engineering and field
Participant 3	>25	Global	Mostly engineering
Participant 4	>10	Russia	Mostly engineering
Participant 5	>15	Russia	Extensive field experience
Participant 6	>25	Global	Extensive field experience
Participant 7	>10	Russia	Mostly engineering
Participant 8	>15	Russia	Mostly engineering
Participant 9	>15	Russia	Extensive field experience
Participant 10	>25	Russia	Mostly engineering

Section 10.1.1. Share of the wells with integrity failures in Russia

The survey question formulates as following: Question 1: What is your best guess of the share (%) of wells with integrity issues in Russia (onshore conventional oil wells), Figure 31.

Figure 31 Questions from the survey (share of the oil wells with integrity issues)

What is your best educated guess of the share (%) of wells with integrity issues in Russia (onshore conventional oil wells) *

1. 10%
2. 20%
3. 30%
4. 50%
5. 75%

Table 9 below presents the answers to the question regarding the wells share with integrity issues. Forty per cent of the participants chose 75%, all those who chose 75% have extensive field experience, which means that they are witnessing the situation firsthand at the oil field. Almost a third of the participants (30%) chose the share of wells with emissions in Russia equal to 50%. It is important to note that none of the participants chose the 10% or 20% share option. According to the survey results, the average value of the proportion of wells with integrity problems is 54%, this value will be used to estimate the total number of wells with integrity problems in Russia, since the average value is the most commonly used parameter to describe the central trend (lumenlearning, 2021).

Table 9 Survey results, share of wells with integrity issues in Russia

	Share of oil wells with integrity issues	Total experience (years)	Geography	Type of experience
Participant 1	75%	>25	Global	Both engineering and field
Participant 2	50%	>10	Russia	Both engineering and field
Participant 3	30%	>25	Global	Mostly engineering
Participant 4	30%	>10	Russia	Mostly engineering
Participant 5	75%	>15	Russia	Extensive field experience
Participant 6	75%	>25	Global	Extensive field experience
Participant 7	30%	>10	Russia	Mostly engineering
Participant 8	50%	>15	Russia	Mostly engineering
Participant 9	75%	>15	Russia	Extensive field experience
Participant 10	50%	>25	Russia	Mostly engineering
Mean	**54%**			
Median	**50%**			
Mode	**75%**			

Section 10.1.2. Share of the wells with integrity issues, which can be restored

The survey question is Question 3: In how many cases well integrity can be restored (%)?, Figure 32. Not all downhole leakages are possible to repair. The share of non-integrities that is possible to repair is restricted technically and economically. One survey participant suggested that all integrity faults are technically possible to repair; however, such repair can cost more than the drilling of the new well. When it comes to cost, there is a hope that increased investment in R&D and higher environmental requirements together will lead to the development of new technologies at a lower cost, which means that a greater proportion of leaks can be recovered at a lower price.

Figure 32 Survey question (share of the cases when the integrity can be restored)

In how many cases well integrity can be restored (%)? *

1. 10%
2. 20%
3. 30%
4. 50%
5. 75%
6. 100%

Table 10 presents the answers to the question of questionnaire No. 3. Participants with a major engineering background chose a higher proportion of integrities that could be restored. A possible reason is that they are more knowledgeable about repairing technologies, including solutions currently in development. The mean value in the results was equal to 59% and was used to assess methane emissions potential reduction.

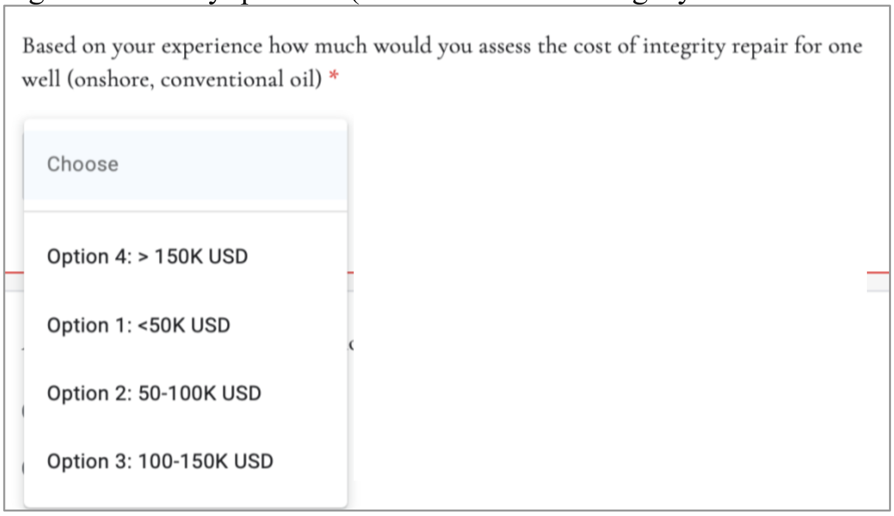
Table 10 Survey results, in how many cases integrity can be restored

	In how many cases well integrity can be restored (%)	**Total experience (years)**	**Geography**	**Type of experience**
Participant 1	10%	>25	Global	Both engineering and field
Participant 2	75%	>10	Russia	Both engineering and field
Participant 3	100%	>25	Global	Mostly engineering
Participant 4	75%	>10	Russia	Mostly engineering
Participant 5	50%	>15	Russia	Extensive field experience
Participant 6	50%	>25	Global	Extensive field experience
Participant 7	50%	>10	Russia	Mostly engineering
Participant 8	75%	>15	Russia	Mostly engineering
Participant 9	50%	>15	Russia	Extensive field experience
Participant 10	50%	>25	Russia	Mostly engineering
Mean	**59%**			
Median	**50%**			
Mode	**50%**			

Section 10.1.3. Cost of integrity repair measures

Question 4: Based on your experience how much you would assess the cost of integrity repair for one well (onshore, conventional oil), Figure 33. A secondary aim of this study is to assess the required costs of remediation measures to repair the non-integrities. It is very difficult to estimate the cost of repairing the leakage in one well because it could be several different non-integrities located at different well depth. The survey participants were asked to assess the cost of repair of one well, Figure 34.

Figure 33 Survey question (estimated cost of integrity restoration of one well)



Source: Own work

Almost half of the participants, 40%, selected the cost option <150 thousand US$ per well. 30% of the participants have chosen the option 50-100 thousand US$ per well. One contributor assessed the cost of repair of one well, less than 50 thousand US$. Table 12 shows answers to the well repair cost question.

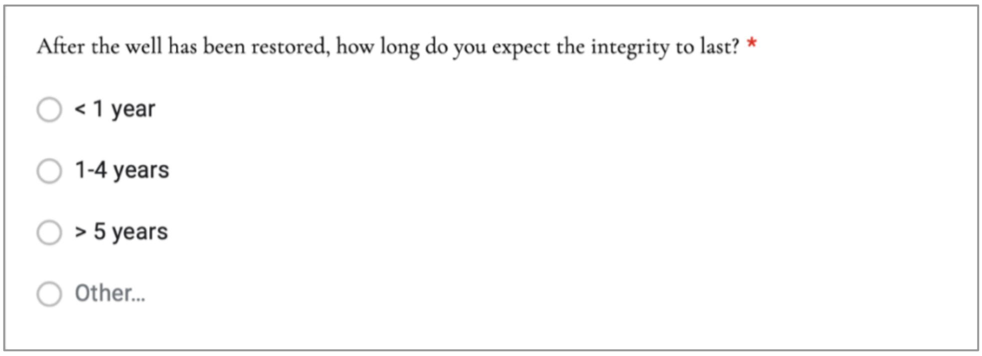
Table 11 Survey results, cost of integrity repair for one well (thousand US$)

	the cost of integrity repair for one well (onshore, conventional oil) Th USD	Total experience (years)	Geography	Type of experience
Participant 1	>150	>25	Global	Both engineering and field
Participant 2	>150	>10	Russia	Both engineering and field
Participant 3	>150	>25	Global	Mostly engineering
Participant 4	50-100	>10	Russia	Mostly engineering
Participant 5	<50	>15	Russia	Extensive field experience
Participant 6	100-150	>25	Global	Extensive field experience
Participant 7	50-100	>10	Russia	Mostly engineering
Participant 8	100-150	>15	Russia	Mostly engineering
Participant 9	>150	>15	Russia	Extensive field experience
Participant 10	50-100	>25	Russia	Mostly engineering

Mean	**113**
Median	**125**
Mode	**150**

Section 10.1.4. Durability of the integrity restoration measures

A question from the survey is: After the well has been restored, how long do you expect the integrity to last? The other important indicator or parameter is the durability of integrity repair measures or for how long the restored integrity can last. Ideally, once the well insolation was successfully restored, well integrity will last sometime after. One of the participants commented that if repair is done correctly, it will last the life of the well and beyond if well operates in non-sour environment and no H2S presence in the reservoir fluid. In some cases, wells are starting to develop leakages right after construction and commissioning. Small leakages can eventually grow to more serious leakages. Unfortunately, no information was found on how long the well has proper integrity after repair.


After the well has been restored, how long do you expect the integrity to last? *

< 1 year

1-4 years

> 5 years

Other...

Figure 34 Survey question (durability of well integrity repair)

Source: Own work

Table 12 presents the question results. Sixty per cent of the contributors selected an option >5 years. Option from 1-4 years was chosen by 40% of the participants. None selected less than a year.

Table 12 Survey results, durability of integrity repair measures (years)

	After the well has been restored, how long do you expect the integrity to last? years	Total experience (years)	Geography	Type of experience
Participant 1	>5	>25	Global	Both engineering and field
Participant 2	>5	>10	Russia	Both engineering and field
Participant 3	>5	>25	Global	Mostly engineering
Participant 4	1-4	>10	Russia	Mostly engineering
Participant 5	1-4	>15	Russia	Extensive field experience
Participant 6	>5	>25	Global	Extensive field experience
Participant 7	1-4	>10	Russia	Mostly engineering
Participant 8	1-4	>15	Russia	Mostly engineering
Participant 9	>5	>15	Russia	Extensive field experience
Participant 10	>5	>25	Russia	Mostly engineering

Mean	**4**
Median	**4**
Mode	**5**

Section 10.2. Share of the wells with non-integrities in Russia

Section 10.2.1. Literature review

The most comprehensive and recent study found is “A portrait of wellbore leakage in northeastern British Columbia, Canada” (Wisen, et al.). Study focuses on well integrity loss-related methane emissions. The research examines data on well leakages received from the British Columbia Oil and Gas Commission (BC OGC), identifies leakage pathways, and quantifies methane emissions from leaking wells. This research is one-of-a-kind to date, and was a central information source for this paper. Report covers wellbore leakages in northeastern British Columbia, Canada (Wisen, et al.). Study concludes that out of 21,525 wells tested for leakage, 2,329 (or 10.8%) reported some integrity issues.

According to Svein Normann (Normann, 2019), the average global share of wells with integrity issues is 19% of all active wells, Figure 35. In the same report, the author indicates that in the Gulf of Mexico and Australia, the wells' share with non-integrities is 45% and 34% respectively.

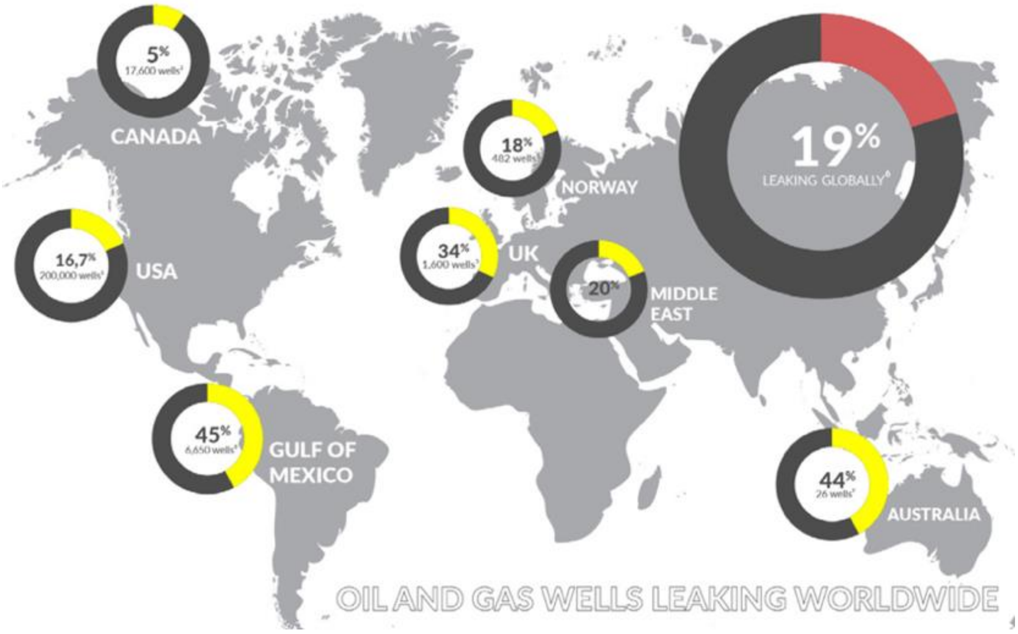


Figure 35 Share of wells with leaks in different regions
Source: (Normann, 2019)

In the study of M.G. Kubrak the problem of well integrity in Russia is mentioned (Kubrak, 2012). The author addresses the issue of idle wells share and discusses the reasons causing it. The report found that 37% of inactive wells are out of production due to casing pipe integrity issues. Although the study is focused on a particular project, it helps to understand the scale of the wellbore leaks in Russia.

Major Russian oil production company JSC "Surgutneftegas" performed the analyses of its well stock and found the share of the wells with serious integrity issues ranging from 40%-80% in different company's entities or 50% on average. Unfortunately, no firsthand research was found. The assumption is made that the study is not available for the public, thus was only mentioned in the industry periodic Rogtechmagazine (ROGTEC, 2019).

Hiber Global is the Company that invented the Hiber Hilo solution to monitor end to end solutions for well integrity. HiberHilo estimates that 30% of the wells globally experience integrity issues (Hiber Global, 2021). Consolidated information on the wells share with integrity issues is presented in Table 13.

Table 13 Wells' share with integrity issues, based on different information sources

#	Source of information	Source	Area/Region/Country	Share of the wells with integrity issues/ methane leaks
1	Report: " A portrait of wellbore leakage in northeastern British Columbia, Canada"	(Wisen, et al., 2020)	British Columbia, Canada	10,8%
2	Article: "The most common causes for leaks in oil wells"	(Normann, 2019)	Global average	19%
3			Gulf of Mexico	45%
4			Australia	44%
5	Study of JSC "Surgutneftegas" (no study found only reference to the study)	(ROGTEC, 2019)	Wells belong to a company	50%
6	Hiber Global	(Hiber Global, 2021).	Global average	30%

Section 10.2.2. Estimated number of the wells in Russia with integrity issues

Number of the wells with integrity issues in Russia was derived by multiplying the total number of the wells (both active and currently idle) by the estimated share of the wells with integrity issues (based on the survey results), Equation 1.

The total number of active wells includes all wells currently in operation. The idle wells are either undergoing capital repairs or awaiting capital repairs Section 8.1 of this study. The latest data on the total number of active wells is as of 2019. However, the newest data on methane emissions reported by Russia is as of 2017. Thus, the number of wells in 2017- -175 000 wells, will be used for reduction estimation. Survey result on the share (%) of wells with integrity issues Section 10.2.1 concludes that the mean wells share with integrity issues in Russia is 54%.

Equation 1. Wells number with integrity issues

$$Wells\ with\ integrity\ issues\ [pcs] = Total\ wells[pcs] * share\ of\ the\ wells\ with\ integrity\ issues\ [\%]$$

$Wells\ with\ integrity\ issues\ [pcs]$=175 000 *54%= **94500 wells**

Section 10.3. Mean methane emission from one well with failed integrity

Methane emissions caused by well integrity failures are divided into SCVF and GM as described in Section 6.4. The majority of leakage incidents (90.7%) are casing gas (SCVF) (Wisen, et al.). GM is very challenging to detect and quantify, due to its geospatial distribution. Figure 36 shows possible pathways of GM. Given the ratio of SCVF to GM in total emissions and the lack of data on the values of the latter, gas migration (GM) will not be taken into account for further estimation of the reduction.

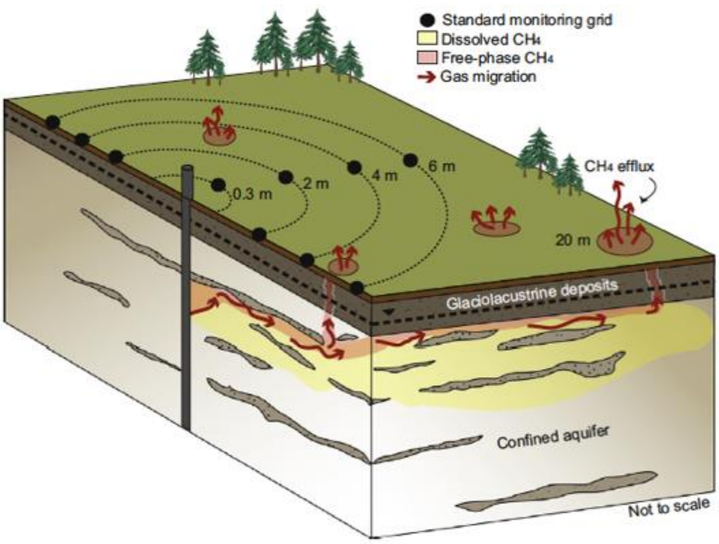


Figure 36 Possible geospatial distribution of GM (gas migration)
Source: (O.N. Fordea; K.U.Mayera; D. Hunkeler, 2017)

The only information on the average SCVF per well was found in the study "A portrait of wellbore leakage in northeastern British Columbia, Canada," published in 2020. For British Columbia, Canada, the average SCVF reported is 5.9 m3 CH4 day from a well, which is equal to a mass rate of 3.87 kg CH4 day from a well or 1.4 tn CH4 day from a well (Wisen, et al.). That information was used in this study for an emissions reduction assessment. Around 90% of leaks measured by mass flow meter were less than 0,7 tn CH4 year from a well, Figure 37 (Wisen, et al.), however even small leakage poses the risk of becoming super emitters.

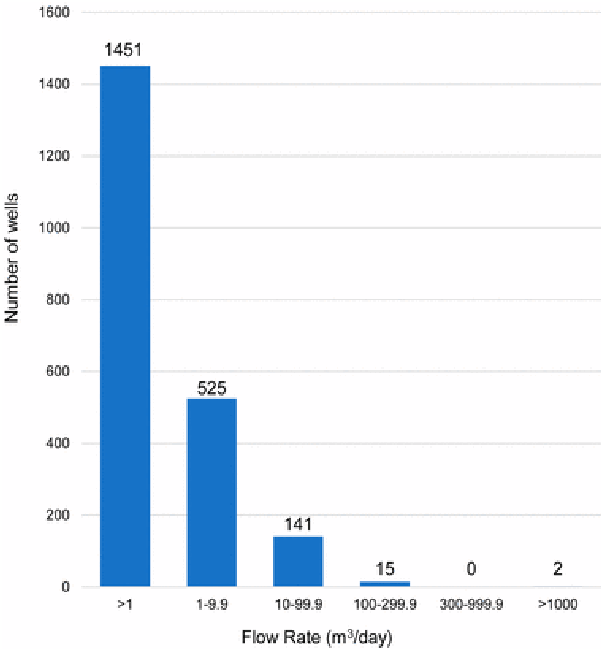


Figure 37 Distribution of reported rates of surface casing vent flows of gas
Source: (Wisen, et al.)

Section 10.4. Share of the integrity issues, which can be completely restored.

Integrity restoration technologies exist and are available on the market. In addition, research and development aimed at integrity issues continues, and numerous startups and new technologies appear on the market, as described in Section 7.2. Some experts (based on the conversations with author) believe that any leakage can be repaired and that well integrity can be restored (100% of leakages are possible to fix). The only issue is cost, which can be enormous, making the restoration of the well not feasible. Companies involved in the integrity restoration business claim a success rate of 80% or more, however, it is common for companies to assess the leakages before admitting the well for the service. As a result, the more serious ones (e.g., leakages caused by casing pipes corrosion with a larger area to seal) are not taken into the service because of the high risk of service failure.

Ninety per cent of experts from the survey believe that a technical limit exists and that not all leakages can be sealed or worth the effort to repair. The same opinion was emphasized in the study by (Wisen, et al.) that concluded that not all leakages are technically possible to repair and what is more important is that not all of them are worth fixing. Accordingly, whether the repair is happening will heavily depend on the oil-producing company or field operator priorities and expenditure structure. It should be taken into consideration that after a leak has started, in most cases, it will continue and expand until the defect is corrected or until the end of the well's life, or even after that for an unlimited period of time.

To assess the technically achievable potential for reducing methane emissions, it is necessary to proceed from the degree of success in eliminating leaks, Equation 2. Based on the survey results Section 10.2.2 the mean value is 59%, meaning that 59% of the wells with non-integrities can be completely repaired.

Equation 2. Number of the wells, where non-integrities can be repaired.

$$Qty\ of\ \ wells, where\ leaks\ can\ be\ repaired = \#\ of\ the\ \ wells\ with\ integirty\ issues\ (pcs) * repiar\ success\ rate (\%)$$

$$Qty\ of\ \ wells, where\ leaks\ can\ be\ repaired = 94500 * 59\% = \mathbf{55\ 755\ wells}$$

Section 10.5. Potential reduction of methane emissions related to integrity losses

Possible methane emissions reduction related to non-integrities is estimated as 78 kt CH4 (Equation 3) if wellbore leakages are repaired and well integrity fully restored.

Equation 3 Potential reduction of methane emissions

$$Potential\ reduction\ of\ methane\ emissions = qty\ of\ the\ wells\ possible\ to\ repair * mean\ methane\ leackages\ from\ one\ well$$

$$Potential\ reduction\ of\ methane\ emissions = 55\ 755\ wells * 1{,}4\ kt\ CH4\ year = \mathbf{78\ kt\ CH4}$$

Potential reduction of methane emissions of 78 kt CH4 a year is an equivalent of **17%** (Equation 4) of the targeted emission group "Oil and venting” **or 1.1%** (Equation 5) of total reported methane emissions, coming from oil and gas activities in Russia. Total reported methane emissions related to oil and gas in Russia were reported at 6,687 kt CH4 a year (Department of Special and Scientific Programs of Roshydromet, 2019).

Equation 4 Potential reduction of methane emissions (out of the targeted group)

$$Potential\ reduction\ of\ methane\ emissions\ (\%) = \frac{Emissions\ reduction\ potential\ \ caused\ by\ wellbore\ leakages}{Total\ targeted\ emissions\ group}$$

$$Potential\ reduction\ of\ methane\ emissions\ (\%) = \frac{78\ kt\ CH4}{462\ kt\ CH4} = \mathbf{17\%}\ \text{reduction of the targeted group}$$

Equation 5 Potential reduction of methane emissions (out of total methane emissions in Russia, coming from oil and gas)

$$Potential\ reduction\ of\ methane\ emissions\ (\%) = \frac{Emissions\ reduction\ potential\ \ caused\ by\ wellbore\ leakages}{Total\ methane\ emissions\ in\ Russia, related\ to\ oil\ and\ gas\ industry}$$

$$Potential\ reduction\ of\ methane\ emissions\ (\%) = \frac{78\ kt\ CH4}{6687\ kt\ CH4} = \mathbf{1,16}\ \%$$

As mentioned in Section 6.1 the easiest and least expensive method to ensure well integrity is proper construction of well barriers system in the first place. Particularly important is the quality of the cementing bond, selection of the casings pipes (overcoming the potential well parameters, such as temperature and pressure). Even though the cost of well construction will increase in the short term (premium material selection and equipment quality), there would be benefits for the oil- producing company in the long term. Such benefits include longer well life and increased oil production because well integrity enables the use of oil enhancement methods such as acid treatments, sidetracking, and or fracturing. On top of the obvious financial and operational benefits for oil producing companies, there is a crucial environmental benefit, fewer methane emissions to the atmosphere, soil, and aquifer. Estimated reduction of integrity loss related emissions are presented in Table 14.

Table 14 Possible reduction of methane emissions due to liquidation of wellbore leakages

Parameter	Data type	Value	Unit
Total oil wells in 2017 including idle	Given data	175.000	pcs
Estimated share of the wells with integrity issues	Estimation based on the survey	54%	%
Estimated share of oil wells in Russia with integrity issues	Calculated	94.500	pcs
Total targeted emissions group of methane emissions (as of 2017)	Including venting on the surface (gas separator for example)	462	kt CH4/ year
Total methane emissions, coming from oil and gas activities in Russia (as of 2017)	Reported emissions	6687	kt CH4/ year
Mean methane emissions from one well	Given data	1,4	ton/year
Estimated emissions related to well integrity failures	Calculated	132	kt CH4/ year
Share of methane emissions related to integrity issues out of total group	Calculated	29%	%
In how many cases well integrity can be restored (%)	Estimation based on the survey	59%	%
Emissions reduction potential caused by wellbore leakages	Calculated	78	kt CH4/ year
Potential reduction of methane emissions (out of targeted group)	Calculated	**17%**	**%**
Potential reduction of methane emissions (out of total methane emissions reported by Russia)	Calculated	**1,17%**	**%**

Chapter 11. Estimated cost of emissions reduction due to well leakages repair and integrity restoration.

This chapter reviews and estimates the costs required to remediate wells' non integrities. To evaluate the economic impact of the implementing measures to the industry in general, the cost is presented in terms of additional spending per ton of oil produced. The distribution of the required costs between the total oil produced in Russia is not entirely accurate, because oil-producing companies own a different number of wells of different ages, with varying levels of production. Because of these variances, some wells in different conditions have more problems with integrity issues and some have less.

Well workovers are classified in Russia as follows. First, routine well maintenance. This is a set of works aimed at restoring the operability of downhole and wellhead equipment, working on changing the well operation mode, and cleaning the lifting string and bottom hole from paraffin-resinous deposits salts and sand plugs by the wellhead team (LLC NSK, 2021).

Second, an overhaul of wells (workover) or KRS (a Russian abbreviation). It is a set of works related to the restoration of the operability of casing strings, cement rings, bottom-hole zone, elimination of accidents, lowering and lifting of equipment during separate operation and injection. In many cases, such workover implies removing and replacing the production tubing string after the well has been killed and a workover rig has been placed on location (LLC NSK, 2021). The interest of this study is in the second type of workover – the overhaul of the wells, which includes measures for integrity restoration (such as casing repair) and secondary cementing (squeezing).

Expenses for an overhaul of the wells continue to increase due to the wells' aging and their increased complexity. In 2018, in Russia, total workover costs increased by 1.5 times vs. 2017 and reached 206.5 bln Rub (3.16 bln US$). For JSC Rosneft expenses increased by 47% and reached 60 bln Rub (1 bln US$) (Deloitte, 2019).

Secondary cementing is a measure to restore the cement bond, this type of service is growing, most likely due to hydraulic fracturing used as a secondary method of increasing oil production. It is important to note that the cost of primary cementing is about 5% of the total cost of well construction, while secondary cementing (pushing) is about 17% of the cost of the well (University of Tulsa's Continuing Education for Science and Engineering , 2021). This fact proves that the best way to ensure well integrity is to do it right at construction potentially reducing future costs by 12%.

The survey revealed that some industry experts believe that there is no technical limitation and any wellbore leakage can be repaired. The main limiting factor is the cost of such repair. Understanding the cost of the proposed measures is critical. However, the following are barriers to cost estimation. Each well has different types of leaks or a combination of leaks, e.g., casing corrosion and channeling in the cement bond; moreover, each leak can be located at a different depth and number of leaks can also differ.

Depending on the size of the leakage (for example, the corrosion size of casing or tubing), the repair price may vary. Some issues can not be repaired at the first attempt. Thus a few well operations may be needed. The durability of the repaired integrity (particularly cement squeezing) could last different periods of time; even if a repair was successful, a new leakage can occur soon after repair. It is difficult to be precise in the estimation of costs because every operation needs an individual approach to equipment used or the combination of equipment needed. Thus, the below calculations are "best possible" estimations to understand the approximate magnitude of these costs.

Section 11.1. Required expenses to implement well integrity restoration measures:

Several parameters need to be defined to estimate the total required workover costs for all wells with integrity problems in Russia. Primarily, the cost of repair of one well should be estimated. As mentioned before, each well may have a different type of leakage or combination of leakages or non integrities. Thus there is no universal average cost applicable for all wells. In the Dusseault study, the average cost of repairing one well is estimated as 150 thousand US$ per well. (Dusseault, Jackson, & Macdonald, 2014). Figure 38 presents a question from the survey related to the cost of remedial operations of one well.

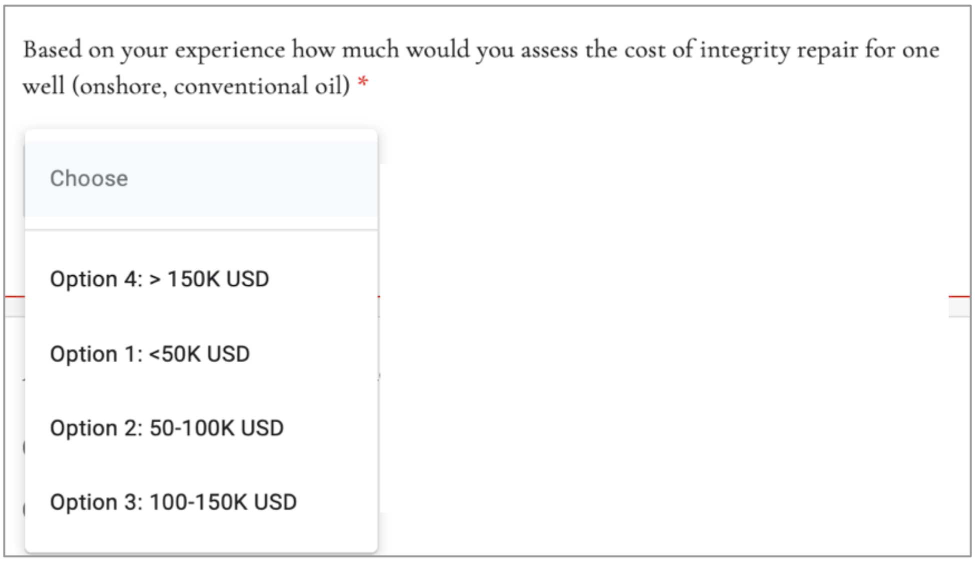


Figure 38 Survey question, estimated cost of integrity restoration of one well
Source: Own work

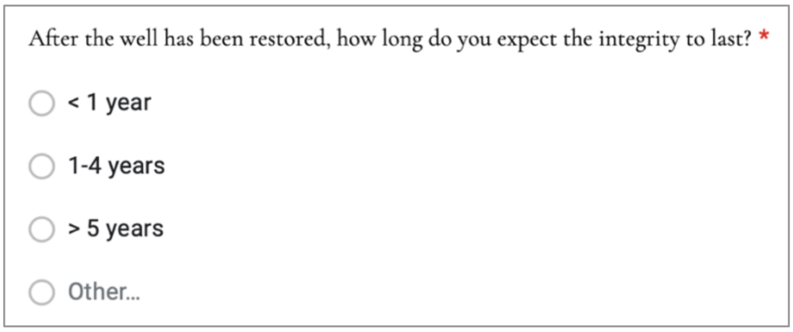
Forty per cent of the survey participants selected the cost of repairing one well as 150 thousand US$ or more; only one participant chose less than 50 thousand US$ (Table 15). To further estimate required expense, the cost of integrity workover per well of 150 thousand US$ will be used. It is necessary to highlight that the cost of the repair does not include expenses related to the location of the leakage, which is an additional expense.

Table 15 Survey results, cost of integrity repair for one well (thousand US$)

	the cost of integrity repair for one well (onshore, conventional oil) Th USD	Total experience (years)	Geography	Type of experience
Participant 1	>150	>25	Global	Both engineering and field
Participant 2	>150	>10	Russia	Both engineering and field
Participant 3	>150	>25	Global	Mostly engineering
Participant 4	50-100	>10	Russia	Mostly engineering
Participant 5	<50	>15	Russia	Extensive field experience
Participant 6	100-150	>25	Global	Extensive field experience
Participant 7	50-100	>10	Russia	Mostly engineering
Participant 8	100-150	>15	Russia	Mostly engineering
Participant 9	>150	>15	Russia	Extensive field experience
Participant 10	50-100	>25	Russia	Mostly engineering

Mean	**113**
Median	**125**
Mode	**150**

The second most important indicator or parameter is the durability of repair measures, i.e., how long the effect of the repaired non integrity can last. The question from the survey is presented in figure 39. Ideally, once the well insolation was successfully restored, well integrity will last for sometime thereafter. In the survey, one of the participants commented that if repair is done correctly, it will last the life of the well and beyond if no H2S presence is in the well.


After the well has been restored, how long do you expect the integrity to last? *

< 1 year

1-4 years

> 5 years

Other...

Figure 39 Survey question, durability of the integrity well repair

In some cases, wells are starting to develop leakages right after construction and commissioning. Small leakages can eventually grow to more serious leakages. Unfortunately, no information was found on how long proper integrity of a well remains after repair. Survey result, Table 16, shows that industry experts selected the option >5 years repaired well seal should last. For the cost estimation, five years was considered.

Table 16 Survey results, durability of integrity repair measures (years)

	After the well has been restored, how long do you expect the integrity to last? years	**Total experience (years)**	**Geography**	**Type of experience**
Participant 1	>5	>25	Global	Both engineering and field
Participant 2	>5	>10	Russia	Both engineering and field
Participant 3	>5	>25	Global	Mostly engineering
Participant 4	1-4	>10	Russia	Mostly engineering
Participant 5	1-4	>15	Russia	Extensive field experience
Participant 6	>5	>25	Global	Extensive field experience
Participant 7	1-4	>10	Russia	Mostly engineering
Participant 8	1-4	>15	Russia	Mostly engineering
Participant 9	1-4	>15	Russia	Extensive field experience
Participant 10	>5	>25	Russia	Mostly engineering

Mean	**4**
Median	**4**
Mode	**5**

Additional operating expenses per ton of oil produced are necessary to understand the full financial implications of the required remediation measures. The total required cost to restore integrity in all wells, where possible, is divided by the sum of the annual oil production over five years (the period of expected persistence of remediation measures), calculations and results in Equation 6. Oil production is publicly available information and published on the Russian Ministry of Energy web page (The Ministry of Energy of the Russian Federation , 2021).

Equation 6 Additional operating expenses per ton of produced oil, after integrity remediation measures were applied.

$$\text{Additional operating expenses per ton of oil}\left(\frac{\text{US\$}}{\text{ton}}\right) = \frac{\mathit{Total\ required\ expenses\ to\ repair\ wells\ with\ leaks}\ (USD)}{\mathit{Sum\ of\ produced\ oil\ over}\ 5\ \mathit{years}\ (2014-2019)}$$

$$\text{Additional operating expenses per ton of oil}\left(\frac{\text{US\$}}{\text{ton}}\right) = \frac{\mathit{Cost\ of\ repair\ one\ well}\ (USD) * \mathit{wells\ can\ be\ repaired}\ (qty)}{\mathit{Sum\ of\ produced\ oil\ over}\ 5\ \mathit{years}\ (2014-2019)}$$

$$\text{Additional operating expenses per ton of oil}\left(\frac{\text{US\$}}{\text{ton}}\right) = \frac{150\ 000\ (usd) * 55\ 755\ (wells)}{2\ 758\ 201\ (thousand\ tons)} = \frac{8\ 363\ 250\ (USD)}{2\ 758\ 201\ (tons)} = 3\ \text{US\$/ton}$$

Repairing all wells currently experiencing integrity estimated to cost more than 8 billion US$ (Equation 6). The assumption is that newly drilled wells are properly constructed, and the well sealing system will last through its lifetime. It is important to consider that the wells' share with integrity issues is a dynamic parameter, meaning it can be changed over time (both growing or decreasing). Cost of locating the non-integrity downhole is not included in the estimation. Additional cost of 3 US$ per ton of oil produced (Table 17) would be required to restore the integrity of wells in Russia to mitigate methane emissions by 78 kt CH4.

Table 17 Estimated cost of emissions reduction per one ton of produced oil

#	Parameter	Data type	units	Value	
1	Number of the wells with integrity issues (which can be restored)	Estimated	pcs (wells)		**55.755**
2	Cost of repair of one well	Estimated	usd/well	**$**	**150.000**
3	Total cost of repair	Calculated	thousand USD	**$**	**8.363.250**
4	How long the effect will last	Estimated	years		**5**
5	Oil production 5 years (2014-2019)	Given	thousand tons		**2.758.201**
6	**Additional spending per 1 ton of produced oil**	**Calculated**	**USD/ton**	**3,0**	

The cost of oil extraction in Russia as of March 2020, including both CAPEX and OPEX was 3-7 US$ per barrel for mature fields and 15-20 US$ per barrel for new fields, Table 17 (Izvestia newspaper, 2021).

Table 18 Cost of oil production in Russia (as of March 2020)

Parameters	Average given costs	Average costs	Units
Average cost of oil production in Russia (2020, mature fields)	3-7	5	USD per Barrel
Average cost of oil production in Russia (2020, new fields)	15-20	18	USD per Barrel
Average cost of oil production in Russia (CAPEX+OPEX) both mature and new fields	**11**		USD per Barrel
Average cost of oil production in Russia (CAPEX+OPEX) both mature and new fields	**82**		USD per ton

Source: (Izvestia newspaper, 2021)

Restored well integrity can potentially reduce methane emissions by 17% or 78 kt CH4 a year out of the targeted emissions group (462 kt CH4 a year), Section 10.6. Given an average cost of oil production of 82 US$ per ton (Table 17) and the required incremental cost of 3 US$ per ton to restore well integrity (Table 16), the overall increase in the cost of oil production is estimated at 4% (Table 19).

Table 19 Average cost of oil production, required additional expenses for remedial measures

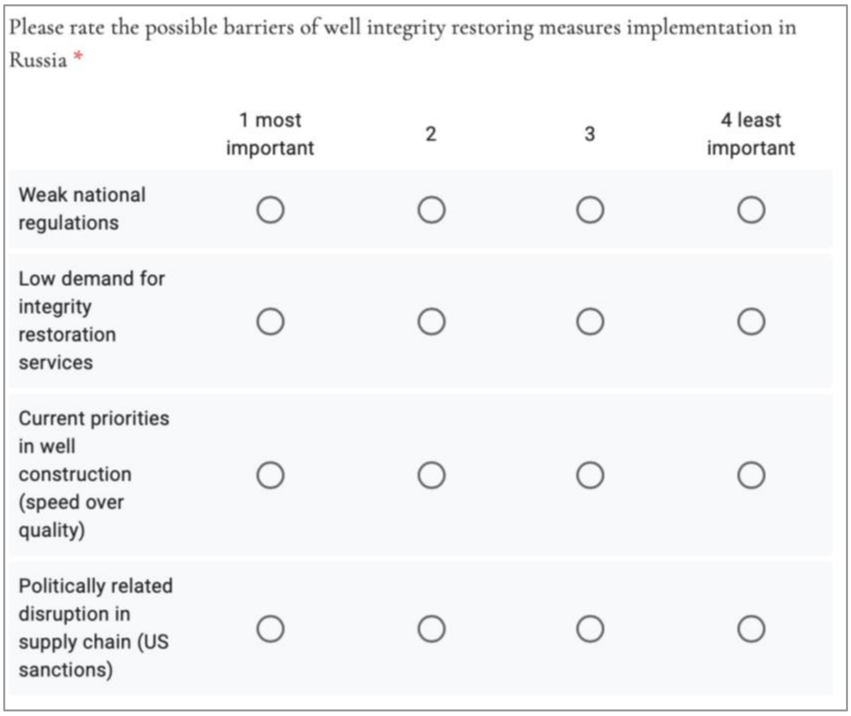
Average cost of oil production in Russia (CAPEX+OPEX) both mature and new fields	**82**	USD per ton
Additional spendings required for integrity restoring measures	**3**	USD per ton
Increase in oil production cost per ton with	**4%**	**%**

The benefits of restoring well integrity include the following: possibility to extend the time of oil production (extended life of well), implementation of production enhancement measures (the wellbore must be properly sealed) such as chemical treatment and hydrofracturing, and environmental benefits in the form of reduced emissions of methane. Some of the idle wells can be brought back to operation and continue production. From the perspective of oil producers, the potential to increase oil production and extend well life is the main benefit from applying remedial measures, while reducing methane emissions is a minor benefit. However, from a societal and climate change perspective, reducing methane emissions is a top priority.

However, it is also important to emphasize, that such an estimation is more theoretical than practical and achievable. Because there are a number of oil producers in Russia, each has a different number of wells in different condition (some have newer wells, some have more mature wells). Financial analyses would be required for each producer to decide on the economic feasibility of implementation of measures.

Chapter 12. Barriers to implementation of reduction measures

The study finds that 17% reduction on integrity losses related methane emission could be tackled. The cost of oil production estimated to increase by 4% or 3 US$ per produced ton of oil. Yet, the problems with well integrity still exist, and companies seem to resist implementing required measures. Therefore, this chapter discusses potential barriers to the employment of remedial integrity measures in Russia. In the survey question (Figure 40), participants were asked to rate potential barriers from "most significant to least significant."


Please rate the possible barriers of well integrity restoring measures implementation in Russia *

	1 most important	2	3	4 least important
Weak national regulations	○	○	○	○
Low demand for integrity restoration services	○	○	○	○
Current priorities in well construction (speed over quality)	○	○	○	○
Politically related disruption in supply chain (US sanctions)	○	○	○	○

Figure 40 Question from survey related to the barriers

The first barrier statement "Weak national regulations for methane emissions" means a lack of national industry regulations for methane emissions caused by integrity issues and integrity management.

There are no specific regulations directly related to well integrity management; however, in general, the condition of the well is strictly regulated. The proportion of wells allowed to be in idle status should be no more than 10% out of the total number of the wells on the balance of oil-producing company. Well abandonment process regulation is well regulated and requires a commission that decides whether the well can be restored, or if the production level is no longer feasible and well should go under P&A (Ministry of Natural Resources of Russian Federation, 2021).

The second barrier statement reads “Lack of demand for integrity restoration services” and could be formulated as a lack of awareness that ventilated methane (SCVF) is a threat to the environment. Oil-producing companies are not always aware of the available solutions or long-term financial benefits of integrity restoring. Small and medium private businesses should introduce such benefits to the oil-producing companies, including National Oil Companies (NOCs), to demonstrate the benefits of integrity management.

The third barrier statement reads, “Priorities of oil-producing companies”. The most effective measure to ensure well integrity is establishing a sealing system from the beginning of the well construction phase to require no corrective action later. However, due to the high cost of drilling and other well construction services, producers often prefer speed over quality, aiming to construct the well as soon as possible and as cheap as possible.

The fourth and final barrier statement reads, “Politically related disruption in the supply chain.” The US and EU imposed targeted sanctions blocking some technologies/solutions to be used in Russia. For example, American companies cannot provide services and supply products to the listed Russian entities/locations/projects, making it more difficult to control emissions.

The results of the survey are presented in Table 19. Most of the participants have selected “Current priorities in well construction (speed over quality)” as the most significant barrier to decrease integrity issues. The barrier “Weak national regulations” was selected as the least significant one. The oil-producing company makes the final decision when choosing a field or well development project. More technologically advanced and high-quality solutions are usually more expensive and take longer to source, and in some cases, they are not available locally. In the participants' experience, oil-producing companies often choose the cheapest and fastest options/solutions and seem to have the wrong Key Performance Indicators; drilling and cementing speed is the number one priority.

Table 20 Survey results, barriers of remedial measures implementation

Barrier	Most significant	2nd	3d	Least significant
Weak national regulations	1	3	3	**4**
Low demand for integrity restoration services	1	**5**	2	1
Current priorities in well construction (speed over quality)	**6**	2	1	2
Politically related disruption in supply chain (US sanctions)	2		**4**	3

In addition to the obstacles already discussed and listed in Table 19, the following barriers to the widespread use of integrity restoration measures are listed. The predominance of national or large oil-producing companies on the market can be a disadvantage. Independent small and medium-sized enterprises (SMEs) provide only 12% oil production as 2019 (Deloitte, 2019).

The international practice has shown that inefficient and problematic wells are purchased by smaller companies, which are usually more flexible and better adapted to technology development. For example, Diversified Gas & Oil PLC (DGO) has a goal to acquire and manage mature natural gas and oil fields and after to maximize production through the deployment of rigorous field management programs by deploying new extraction technologies (Diversified Gas & Oil PLC, 2021). The disadvantage here is the possible bankruptcy of SMEs and the lack of further extended liability for abandoned wells.

One more possible barrier is the lack of competition between service companies. Among the service companies in Russia, there are: Global "giants" (Schlumberger, Halliburton, Weatherford, Baker Hudges). Next, there are the companies formed based on territorial industry organizations that existed in Soviet times. The last group is service companies that were separated from oil-producing companies in the 1990s, such companies become depended on oil producers. In bulk, up to 75% of oil and gas companies in Russia continue to provide services through their subdivisions (ERTA consult, 2021). In this case, such service companies have a guaranteed work without competition and have little or no incentives to improve services/upgrade equipment/educate people.

The last barrier to mention is that no extended responsibilities exist for well services/suppliers involved in well construction, particularly well cementing. After a well is completed, there is a compulsory integrity test (immediate after construction and before the well is commissioned). However, a well can demonstrate integrity issues (such as build-up casing pressure) in a couple of months/years after exploitation. In this case, none of the well construction contractors will hold any responsibility (Rogtecmagazine, 2021). This situation is partially caused by the complexity of the business structure and material purchasing regulations. (e.g., the company who provides cementing service have no right to choose the casing pipe suppliers and thus, will not take responsibility for the whole service, plus they must accept responsibility for wells after drilling).

Chapter 13. Conclusion and policy implications

Reducing methane emissions related to well integrity failures can be a matter of making simple changes to operational practices and better selection of materials and equipment. With the gradual depletion of conventional oil reserves, new reserves would require wells with complex trajectories, longer wells with more elements at the bottom hole assembly. As for the existing well stock, the proportion of wells with integrity problems is expected to grow as material fatigue, corrosion, and so on set in. All these factors create conditions for an increase in methane emissions due to failing well integrity.

This study finds that it is possible in Russia to reduce methane emissions by 78 kt CH4 per year, Figure 41 which is 17% of the category "oil and venting" from the oil upstream segment in Russia (emitting 462 kt CH4 per year in 2017 according to the National Inventory Report), Section 10.6. To implement remedial measures additional expenses required are estimated at 3 US$ for each ton of oil produced, Section 11.1 . Considering that the average cost of oil production in Russia (from both mature and new oil fields) is 82 US$ per ton, the cost of production is estimated to increase by 4%. However, it must be taken into account that this is for the country as a whole, in reality production from some oil fields is more expensive than from others. Also, different oil producing companies have different numbers of wells and those wells are a different condition, have production level and oil/water/gas production ratio.

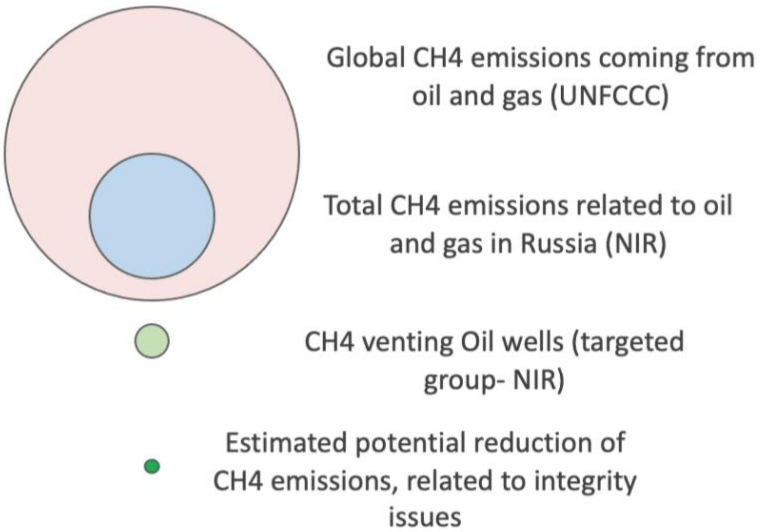


Figure 41 Vizualization of the emissions reduction potential

Oil wells with no integrity issues have a series of advantages for oil producing companies and oil producers should have a direct economic interest to ensure the integrity from the stage of well construction. The main advantages of a properly insolated oil well are as follow: extended life length of well since with intact integrity, oil intensification methods can be applied and oil production increased. On top of that, if no integrity issues, oil producing companies will avoid expenses required by national regulations to restore integrity for each well before plugging and abandonment.

Technologies capable to detect and fix the non-integrity downhole issues exist, however, they have a number of disadvantages and require further developments. For example, several companies offer promising alternative materials to restore cement collar such as polymers-pressure/temperature activated, resins Section 7.2.1. Some service companies, before agreeing to provide integrity repair services assess the type and location of non-integrity issues. Depending on form and nature of non-integrity, companies agree or decline to provide the repair service. And even then, there is no guarantee that integrity will be restored. For example, cement squeezing jobs, sometimes require three- five runs (SPE, 2021) before successful restoration. In some cases, wells are out of operation during the restoration service. Said above, again emphasizes the importance of ensuring the integrity from the construction stage of the well.

A conclusion of this study is that there is a potential market in Russia for integrity restoration services. In production regions with mature oil fields such as western Siberia, an existing infrastructure is in place (roads, bridges, pipelines, railroads, airports, etc.). For the wells located in that region, enhancement production methods can be applied (hydrofracturing, acid treatment, etc.) proving that well integrity issues must be addressed simultaneously. A relatively large number of wells in the region are 10-15 years old, meaning they are in a high-risk group for developing integrity failures. Oil producers face a choice to repair existing well or to drill a new one. It can be cheaper to address the integrity issues in existing wells and deploy oil enhancement methods, rather than to invest in the building of infrastructure to develop new fields. For example, new projects in East Siberia (Irkutsk region and Yakutia) require enormous investments, mostly for infrastructure development (roads, bridges, etc.). JSC "Surgutneftegas" had to build a private airport capable to land Boeing 737 planes (Wikipedia, 2021) to somehow solve the logistical issues in the region. Ensuring the wells' integrity from the beginning is the most sustainable and economically efficient way of field development, and oil-producing companies ought to be directly interested.

To address the issue of wells with integrity issues and mitigate associated methane emissions, the author of this study proposes that an action plan be developed and implemented at the government level to review/and or update industrial regulations. Special criteria could be developed to identify wells with higher risk for integrity failure and these are to be selected for special scrutiny measures. Factors identified in this study as risk factors for well integrity issues are presented in Table 5. The author of this study would further propose that each oil producer review and assess its well stock about every five years (to select wells with higher risk of integrity failures and associated methane emissions). Overall, the following recommendations can be made: creation of baseline indicators of well integrity status, establish an industrial standards and a workflow to manage well integrity issues and adopt a proactive approach to well integrity for growing well stock.

For newly constructed wells, extended responsibilities could be developed and applied to the service companies. In this case service providers would not only guarantee an immediate integrity (after construction, pressure test and prior to well commissioning) but also guarantee integrity after two-three years of well operation. Service providers will then be more alert about the quality of work and materials selection. Currently there is an existing practice of fines applied to service providers, reaching up to 20% of the cost of service or product but no extended responsibilities (from the author's own experience working in the industry).

Another important problem in the fight against methane emissions due to leaks in wells is political, particularly sanctions and a ban on the supply of technologies and materials to Russian oil and gas companies. If technologies are aiming to improve the state of the environment, they should not be a subject to sanctions. Since methane is a greenhouse gas and a precursor to ozone that knows no boundaries when released in one country, will impact climate and air quality in others, thus, it should be addressed as a common global problem.

On top of that, measures to reduce associated gas (APG) can be applied. Such measures can drastically decrease the production of unwanted gas (APG) and simultaneously increase the production of oil. For example, InflowControl AS provides the case where the installation of AICVs (Autonomous Inflow Control Valve) in a mature well, lead to 85% reduction in gas production and five times increase in oil production. (InflowControl AS, 2020).

Overall, it is not expect that solving the problem of well integrity can solely solve the problem of climate change or methane emissions from the oil and gas sector, but certain share of methane emissions can be removed without additional capital investment, while in the long term, operators can even earn money by extending the lifetime of the wells.

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Appendix: Survey questions & Glossary

Well integrity and methane emissions in Russia

Oil well integrity failures are a common. Integrity loss lead to methane emissions in two major forms SCVF (surface casing vent flow) and GM (gas migration). As of today, little information is available on the volumes of emitted methane caused by well integrity losses and consequently it is difficult to understand the mitigation potential of such emissions.

The aim of my research is to assess the reduction potential of SVCF (surface casing vent flow) and estimate the required cost.

***Well Integrity defines as "the application of technical, operational and organizational solutions to reduce the risk of uncontrolled release of formation fluids throughout the life cycle of the well" NORSOK Standard D-010 definition

* Required

Your name *

Your answer

What is your best educated guess of the share (%) of wells with integrity issues in Russia (onshore conventional oil wells) *

Choose

In your opinion what is the most efficient (cost/labor intensive and safe) way of SCVF (surface casing vent flow) detection and monitoring *

- Option 1: Shortly after production started, then 5 years after production, lastly, prior the abandonment
- Option 2: Monitoring of SCVF every 2nd year after production started
- Option 3: Monitoring of SCVF only if visual signs of methane emission present
- Option 4: Continues SCVF monitoring (IIOT) flow meters for every well

In how many cases well integrity can be restored (%)? *

Choose

Based on your experience how much would you assess the cost of integrity repair for one well (onshore, conventional oil) *

Choose

After the well has been restored, how long do you expect the integrity to last? *

- ○ < 1 year
- ○ 1-4 years
- ○ > 5 years
- ○ Other: ________

In your opinion, what is most important for SCVF (Surface Casing Vent Flow) mitigation? *

- ☐ Implementation of VRU (Vapor Recovery Unit) to compress gas streams fro use in a local site fuel gas system or directly into a gas gathering line
- ☐ Stricter regulations and improved standards to ensure "Doing it right the first time" approach
- ☐ Investments in development of remediation technologies (resins, polymers, temperature patches etc.
- ☐ Continues, autonomous, independent monitoring of SCVF (Surface Casing Vent Flow)
- ☐ Other: ________

Please rate the possible barriers of well integrity restoring measures implementation in Russia *

	1 most important	2	3	4 least important
Weak national regulations	○	○	○	○
Low demand for integrity restoration services	○	○	○	○
Current priorities in well construction (speed over quality)	○	○	○	○
Politically related disruption in supply chain (US sanctions)	○	○	○	○

Gathering system

The flowline network and process facilities that transport and control the flow of oil or gas from the wells to a main storage facility, processing plant or shipping point. A gathering system includes pumps, headers, separators, emulsion treaters, tanks, regulators, compressors, dehydrators, valves and associated equipment. There are two types of gathering systems, radial and trunk line. The radial type brings all the flowlines to a central header, while the trunk-line type uses several remote headers to collect fluid. The latter is mainly used in large fields. The gathering system is also called the collecting system or gathering facility (Schlumberger, n.d.)

Annulus

The space between two concentric objects, such as between the wellbore and casing or between casing and tubing, where fluid can flow. Pipe may consist of drill collars, drillpipe, casing, or tubing (Schlumberger, n.d.)

Casing

Large-diameter pipe lowered into an openhole and cemented in place. The well designer must design casing to withstand a variety of forces, such as collapse, burst, and tensile failure, as well as chemically aggressive brines. Most casing joints are fabricated with male threads on each end, and short-length casing couplings with female threads are used to join the individual joints of casing together, or joints of casing may be fabricated with male threads on one end and female threads on the other. Casing is run to protect freshwater formations, isolate a zone of lost returns or isolate formations with significantly different pressure gradients. The operation during which the casing is put into the wellbore is commonly called "running pipe." Casing is usually manufactured from plain carbon steel that is heat-treated to varying strengths but may be specially fabricated of stainless steel, aluminum, titanium, fiberglass, and other materials (Schlumberger, n.d.)

Cement

The binding material in sedimentary rocks that precipitates between grains from pore fluids. Calcite and quartz are common cement-forming minerals (Schlumberger, n.d.)

Pressure gradient

The change in pressure per unit of depth, typically in units of psi/ft or kPa/m. Pressure increases predictably with depth in areas of normal pressure. The normal hydrostatic pressure gradient for freshwater is 0.433 psi/ft, or 9.792 kPa/m, and 0.465 psi/ft for water with 100,000 ppm total dissolved solids (a typical Gulf Coast water), or 10.516 kPa/m. Deviations from normal pressure are described as high or low pressure (Schlumberger, n.d.)

Downhole safety valve (DSV)

A downhole device that isolates wellbore pressure and fluids in the event of an emergency or catastrophic failure of surface equipment. The control systems associated with safety valves are generally set in a fail-safe mode, such that any interruption or malfunction of the system will result in the safety valve closing to render the well safe. Downhole safety valves are fitted in almost all wells and are typically subject to rigorous local or regional legislative requirements (Schlumberger, n.d.)

Secondary cementing

Another term for remedial cementing operations performed to repair primary-cementing problems or to treat conditions arising after the wellbore has been constructed. The two main categories of remedial cementing include squeeze cementing and the placement of cement plugs (Schlumberger, n.d.)