CARBON LIMITS

Methane abatement potential from oil and gas systems in Kazakhstan

CARBON LIMITS

This paper was prepared by Carbon Limits AS.

Title:
Methane abatement potential from oil and gas systems in Kazakhstan

Finalized:
28/03/16

Project:	Methane Programme in Kazakhstan
Funded:	ClimateWorks
Project leader:	Stephanie Saunier
Project members:	Hesam Darani, Irina Isakova, Martin Gallardo Hipólito

There is limited knowledge about the scale and characteristics of the oil and gas sector methane emissions outside of North America. It is widely agreed that this represents a major barrier to the development of methane emission reduction strategies. This paper presents the results of a project to improve the knowledge on methane emissions and emission reduction opportunities in an important oil and gas producing country: Kazakhstan. The analysis is based on extensive Kazakh-specific data, derived from (i) the results of measurement campaigns in upstream and midstream facilities and (ii) the answers in response to a questionnaire covering current practices and equipment count.

Overall, the analysis estimates methane emissions in the upstream and midstream sectors in Kazakhstan at 6.6 million tons of CO_2 equivalent ($MtCO_2e$) or about 12.7 billion cubic feet of methane per year. At least 1.6 million tons of CO_2 equivalent each year can be reduced at a negative abatement cost (i.e. the savings from the gas recovered exceed the project's implementation costs).

Acknowledgements:
The project team would like to thank the different Kazakh stakeholder organizations for providing numerous inputs for the preparation of this paper. In particular, we would like to acknowledge with much appreciation the crucial role of the staff of KazMunayGas for their continuous support throughout this project.

Acronym

Bcf	Billion cubic feet
Bcm	Billion cubic meters
CAPEX	Capital expenditure
CCAC	Climate and Clean Air Coalition
EF	Emission factor
EPA	US Environment Protection Agency
ETS	Emission Trading System
GHG	Greenhouse gas
GWP	Global warming potential
IEA	International Energy Agency
IIASA	International Institute for Applied Systems Analysis
IPCC	Intergovernmental Panel on Climate Change
KMG	KazMunayGas
$KtCO_2e$	Thousands tons of CO_2 equivalent
MMscf	Million standard cubic feet.
$MtCO_2e$	Million tons of CO_2 equivalent
nmVOC	non-methane volatile organic compound
OPEX	Operating expenditure
tCO_2e	Tons of CO_2 equivalent
VRU	Vapor recovery unit

1. Introduction

1.1 Background and rational

The research presented in this note, supported by a grant from ClimateWorks, was motivated by the knowledge gap on methane emissions and abatement opportunities in the oil and gas sector. While current emission estimates are high – 20 to 30% of anthropogenic methane emissions across all sectors (Sources 28 and 4) – and abatement potentials are thought to be significant (Source 28), few empirical studies have been conducted outside of North America.

Kazakhstan has been chosen for this research for several reasons:

- The country is a major oil and gas producer and is located at a crossroads between Europe and Asia, ideal for gas supplies.
- The national oil and gas industry of Kazakhstan has shown keen interest in the issue of resource loss and environmental damage caused by methane emissions and has demonstrated its readiness to incorporate the knowledge acquired into development of a methane emission reduction strategy.
- The authorities of Kazakhstan have also expressed interest and indicated that efforts to reduce methane emission reductions might be included in their forthcoming submission of the NDC (Nationally Determined Contribution) under the Paris Agreement.

This project is an integral part of a larger methane program which focuses on methane abatement in the Kazakh oil and gas sector.

1.2 Background on Kazakhstan oil and gas production and infrastructure and climate policy

Kazakhstan's proven crude oil reserves are currently assessed at about 30 thousand million barrels (Source 32). Thus, Kazakhstan represents the second largest reserves in Eurasia after Russia, and the twelfth largest in the world, just behind the United States. Kazakhstan had around 1.5 trillion cubic meters of proven natural gas reserves in 2014 (Source 32), the majority of which are in crude or condensate-rich fields.

Kazakhstan is a major oil producing country with a crude oil production of around 1.70 million barrels per day (bbl/d) in 2014, which have been fairly stable over the last few years (Source 32). There are currently 172 oil fields and 42 gas condensate fields in Kazakhstan, but the current oil production is dominated by two giant onshore fields: Tengiz and Karachaganak, which produce about half of Kazakhstan's total petroleum liquids output (Source 32). Over the past decade, natural gas production in the country has increased by about 50%, up to 19.3 billion cubic meters in 2014.

Traditionally, Kazakhstan has been exporting gas to Russia both from Karachaganak field and via the Central Asia-Centre pipeline. Kazakhstan is also a major transit country for exports from Turkmenistan and Uzbekistan. The volume of international gas transit through Kazakhstan in 2014 amounted to 78.6 billion cubic meters (Source 13). All gas transportation is carried out by the JSC "KazTransGas" (fully-owned subsidiary of KazMunaiGaz) and its affiliated companies. There are more than fifteen gas processing plants in the country, but only a few represent the major share of the capacity.

Kazakhstan is a regional leader on climate mitigation and has committed to 15% reduction from 1990 greenhouse gas levels by 2020. In January 2013, the country launched an ETS covering CO_2 emissions from the energy sector (including oil and gas), mining and chemical industry. Methane emission reduction projects can be used as offsets under Kazakhtan's ETS.

1.3 Objective of the work

Based on methane emission measurements and other information from field operators in Kazakhstan, as well as a number of secondary sources, this research aimed to provide robust estimates of:

- Methane emissions from upstream and midstream oil and gas systems in the country
- Methane abatement potential
- Abatement costs for a range of mature emission control technologies

The project is expected to allow companies and authorities of Kazakhstan to i) realize the significance of methane emissions, ii) identify the most attractive abatement opportunities in the country, and iii) promote large-scale solutions to address the high abatement potential. The project also aimed to use the Kazakhstan example to begin developing a methodology to improve emissions inventories and describe abatement potential for other countries outside North America.

The paper is organized in three main sections:

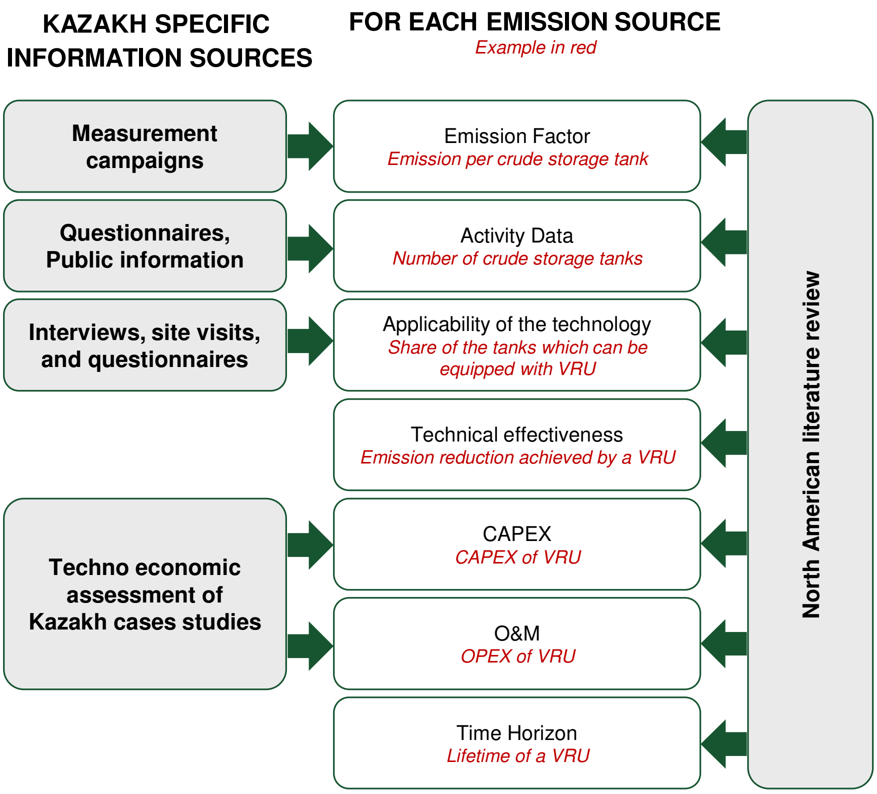
- Section 2 describes the sources of information used in the analysis.
- Section 3 provides a description of the methodology applied in the analysis.
- Section 4 presents the results of the assessment.

2. Sources of information

2.1 Overview of the information sources

The analysis of methane emissions and the abatement potential in Kazakhstan relies on new empirical data collected though measurement campaigns, other existing data from Kazakhstan and results from international, primarily North American, studies. Further, the work is based on knowledge and experiences shared by industry experts in Kazakhstan through questionnaires and formal and informal interviews. Figure 1 below summarizes key information categories for the methane emissions abatement, abatement cost estimates and the relevant sources that were used. Additional sources of information are further described later in this paper.

Figure 1: Information source overview



2.2 Kazakh-specific sources of information

Methane and VOC emissions measurement campaigns

The first important source of the country-specific data was direct field measurement campaigns. In autumn 2015, Carbon Limits performed leak detection and repair campaigns at several upstream (well sites, treatment units, processing plants), midstream (compressor stations) and downstream facilities (distribution stations). Over two weeks, the project team directly detected, measured, and quantified methane and nm-VOC losses from site installations, which allowed for better understanding of the existing infrastructure, common practices and technical applicability of methane reduction solutions. The measurement campaigns covered a total of six large installations and many small dispersed facilities (e.g. small well sites, gas regulation stations, and distribution blocks). The installations covered are not necessarily representative of the full population of installations in Kazakhstan, and the number of installations covered does not allow for statistical utilization of the emission factors derived. However, these measurement campaigns provided a unique insight into the actual emissions factors for different types of equipment (e.g. measurement covered seven storage tanks).

Questionnaire and interviews on activity and current practices.

Close cooperation with KazMunayGas (KMG) also enabled further assessment of activity data and applicability of various emission reduction technologies by compiling and reviewing the results of a questionnaire. Activity information and current practices were collected from 12 different companies, covering over 80% of country's gas transportation and oil refining, as well as about 25% of oil production and 14% of gas processing. The questionnaire covered a range of questions, including the number of wet or dry seal compressors, information on the frequency of blowdown or well fracturing, the types of controller devices used, etc. Questionnaire answers were corroborated by phone or face-to-face interviews with technical experts in Kazakhstan to confirm assumptions on the current practices in the country.

Techno-economic assessment of emissions reduction projects in Kazakhstan

As part of the collaboration with KMG, Carbon Limits performed techno-economic assessments of emissions reduction projects in Kazakhstan. These detailed analyses provided background for realistic estimates of investment and operational costs of various emission reduction technologies. Leading supplier quotes were obtained for various solutions to establish reliable assumptions regarding CAPEX and O&M costs.

Other sources of information
Activity data were verified through in-depth analysis of publicly available information (both in English and Russian). This included statistical and analytical reports of the Ministry of Energy of the Republic of Kazakhstan and its relevant departments (Department of subsoil management, oil and gas industry development), oil and gas companies' annual reports (KazMunayGas, KazTransGas, Tengizchevroil), as well as articles and other publications by industry associations (KazEnergy).

2.3 Literature review of emission factors and best practices not specific to Kazakhstan

Though Kazakh-specific information was preferred for the analysis, there was not always sufficient information to estimate robustly each assumption. To fill in the gaps, North American literature was used to supplement information from Kazakhstan. The following sources of information were used amongst others:

- Global Mitigation of Non-CO_2 Greenhouse Gases, 2010-2030, EPA, 2014
- Quantifying Cost-effectiveness of Systematic Leak Detection and Repair Program Using Infrared Cameras, Carbon Limits, 2014
- Economic Analysis of Methane Emission Reduction Opportunities in the U.S. Onshore Oil and Natural Gas Industries, ICF, 2014

Though North American literature was used to derive some emissions factors, as there were only a few in-country measurements, the project team worked to ensure that the activity factors were based on Kazakh-specific information and did not rely on American proxies (i.e. typical number of dehydrators per well in the US).

The complete list of the assumptions and the sources of information used for each assumption are presented in Annex 1.

3. Approach and methodology

3.1 Overview

The figure below provides an overview of the methodology applied for this study. During the first step of the process, the project team defined emission categories and subcategories relevant for Kazakhstan. Emissions were then quantified for each subcategory using both activity and emission factors.

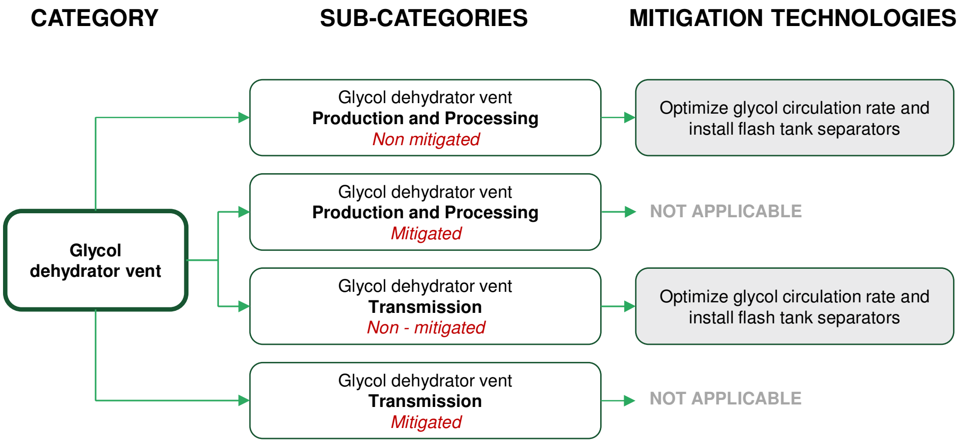
A key part of the study was to document, as accurately as possible, emissions in the country using answers from the questionnaire, measurement campaign results, and consultations with oil and gas experts in the country. When needed (and available), an abatement technology was matched to each emissions subcategory, and both the abatement cost and abatement potential were estimated. Lastly, the results were compiled and quality checked.

Figure 2: Overview of the methodology applied

3.2 Definition of the emissions source categories and subcategories

During this first step, the methane emission sources were divided into categories and subcategories. Existing typology of emissions sources (e.g. CCAC nine core emissions sources) were used as a starting point. The same level of desegregation was then adapted to Kazakhstan data. When relevant (e.g. when the emissions were not already mitigated), a mitigation technology was then matched with each emission subcategory. (See figure below for an example)

Figure 3: Definition of the categories and subcategories - Dehydrator example



3.3 Quantification of the emissions

For each emission subcategory *i*, the magnitude of emissions in Kazakhstan (in MMscf) was estimated as follows:

$$Emission_i = Activity\ Factor_i * Emission\ Factor_i$$

For each emissions source subcategory, **activity factors** such as number of crude storage tanks or gas volume burned in gas engines were estimated. Activity factors were evaluated based mainly on (i) general literature review in Kazakhstan, (ii) the questionnaire answers gathered, and (iii) overall observation of the status of existing emission sources during on-site campaigns and expert consultations.

Equipment count (e.g. number of pumps, number of compressors) from many of the facilities in Kazakhstan was derived from the questionnaire answers. Information for facilities not covered in the questionnaire was extrapolated based on questionnaire answers and depending on type of facility (size, age, etc.)

Emissions factors (volume of methane emitted per activity factor e.g.MMscf/crude storage tank) were derived from the combination of the measurement campaigns and emissions factors in the current literature. The measurement campaigns provided crucial insight into the emission range, yet the sample of facilities covered was limited and not all types of emissions categories could be directly measured (for example, the measurement campaign did not cover any liquid unloading events). When this occurred, emissions factors from the literature and from Carbon Limits database (Source 10) were used.

3.4 Quantification of the abatement potential

For each subcategory *i*, the abatement was estimated based on the following equation:

$$Abatement\ Potential_i = Emission_i * Applicability\ of\ the\ technology_i * Reduction\ efficiency\ _i,$$

where

The applicability of the technology (in %) represents the share of the total emissions from a particular emissions subcategory to which the abatement technology can be applied. The applicability was generally estimated by experts, based on field experience and interviews with oil and gas experts[1].

Reduction efficiency (in %) represents the percentage of technically achievable emissions reduction for an abatement technology, after it has been implemented. The reduction efficiency was generally estimated based on existing literature (Source 3, 4 and 5).

3.5 Quantification of the abatement costs

Finally, the abatement costs, from a company perspective, were estimated for each subcategory *i* as follows:

$$Abatement\ Cost_i = -\frac{Discounted\ sum\ of\ cash\ flow\ per\ facility}{Discounted\ emission\ reduction\ per\ facility}$$

The discounted cash flow for one facility was calculated as follows

$$-CAPEX + \sum_{t=1}^{T} \frac{-OPEX + Volume\ of\ gas\ saved * Gas\ price}{(1 + interest\ rate)^t}$$

And finally, the volume of gas saved was estimated as follows:

$$Volume\ of\ gas\ saved = \frac{Methane\ emissions\ * \ Reduction\ efficiency}{Share\ of\ methane\ in\ the\ gas\ stream}$$

Where

- **CAPEX** represents the capital costs to implement the abatement technology and **OPEX** includes all the changes in operational costs compared to the baseline. When feasible, CAPEX and OPEX estimates were derived from emissions reduction projects in Kazakhstan. Costs estimates from international literature were also used.
- **Share of methane emission in the gas stream** was estimated based on (i) the measurement campaigns and (ii) information on typical gas composition in Kazakhstan (see table below).
- **Gas price** was evaluated for each sub-segment (see table below) and set at zero when the gas saved could not be recovered. Sensitivity on gas price is presented at the end of this paper.
- **T** represents the lifetime of the technology, which was typically estimated based on existing international literature (Source 3, 4 and 5).

Table 1: Summary of the assumptions on gas price and share of methane in the gas stream

	Gas price (USD/Mscf)	Share of methane (%)
Production	2	80%
Processing	3	96%
Transmission	3	87%

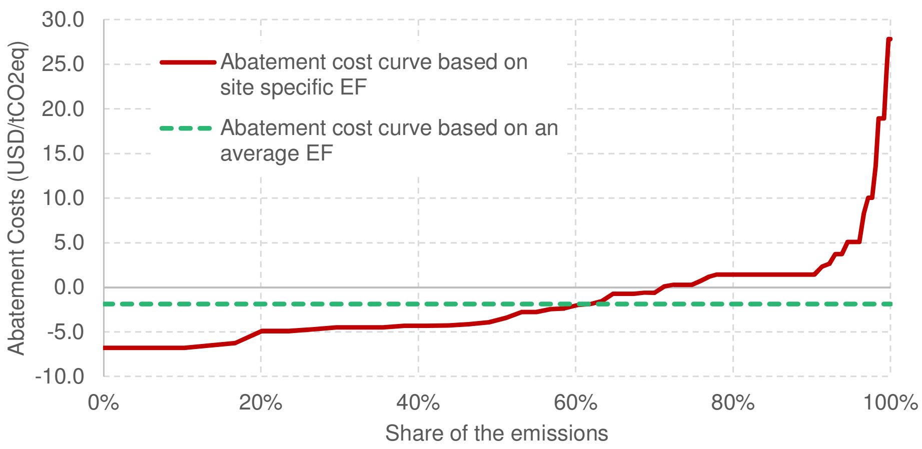
[1] Conservative estimates (low applicability) were favored and the resulting abatement potential is thus likely underestimated.

BOX: Variability of the abatement costs – Description of the methodology applied

Methane abatement costs in the oil and gas sector are, by nature, site specific and depend on (i) the actual emissions factors for a specific equipment/site and (ii) the site-specific costs for the project implementation.

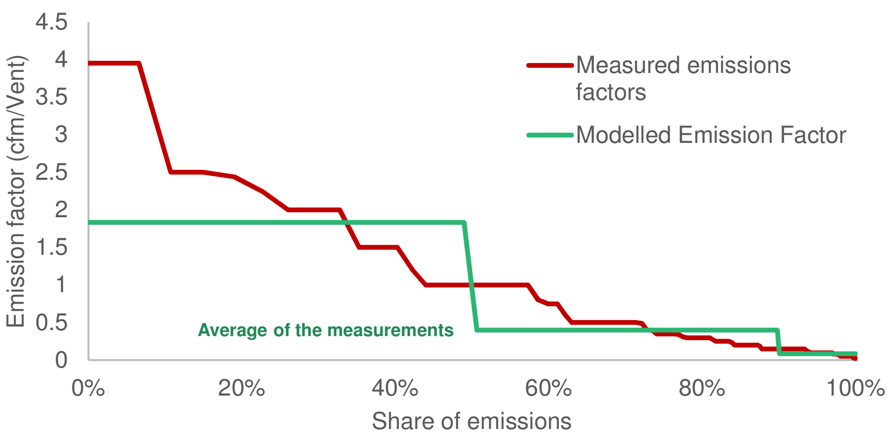
The following figure illustrates the variability of the abatement costs for 62 pumps in US and Canada. The abatement cost estimated based on the average EF misrepresents the site-specific abatement costs for a large share of the facilities. In this example, the abatement costs is positive for almost 60% of the pumps evaluated, while the abatement costs based on the average EF is a negative.

Figure 4: Abatement costs for a sample of injection pumps- North America – Illustrative



To handle this issue, three different EFs (average, high and low) have been modelled for this project. The following figure presents the modelled EF compared to the measured EF. The weight of the three different EFs (i.e. the share of total emissions associated to the EF) has been estimated based on typical EF distribution in North America.

Figure 5: Distribution of EF - Real versus modeled - Illustrative based on 152 Rod Packing Vent in North America[2]



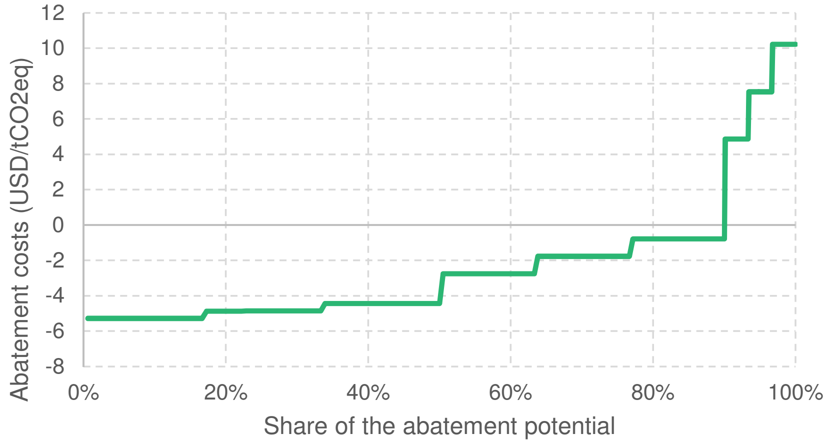
The variability of the CAPEX has also been modelled, with three levels of CAPEX (average, low and high), which are assumed to be equally probable.[3]

An abatement cost curve is thus generated for each emissions subcategory. Figure 6 illustrates the abatement cost distribution for chemical injection pumps in Kazakhstan.

[2] The approach has been tested on eight distributions of EFs from measurements in the US and Canada.

[3] Technology efficiency variability was also modelled but was found to have a very limited impact on the abatement cost distribution.

Figure 6: Distribution of EF - Real versus modeled - Illustrative based on 152 Rod Packing Vent in North America[4]



3.6 Result compilation and quality review

The emissions, abatement potential and abatement costs were then calculated and compiled for each emission subcategory. The model developed for this task allows combining all the assumptions and specifying the portion that can be addressed by a mitigation technology. The results were then compared to the existing national inventory of Kazakhstan and emissions intensity were derived (emissions per unit of production for example). These were then compared to other international emissions intensities.

3.7 Caveats and limitations

The estimates were based on extensive research and analysis, and effort has been made to base the estimates on the most plausible assumptions. However, a number of caveats and limitations need to be highlighted.

Excluded emission sources: Some sources of emissions, such as casing gas emissions and blowdown from upstream (gathering) pipelines, were not presented in this paper[5] due to the lack of Kazakh-specific information. These emission sources may represent interesting abatement potential, which should be evaluated further.

Number of installations covered during the measurement campaigns: As described above, the measurement campaigns covered six large installations and a number of smaller sites. The installations covered are not necessary representative of the total population of installations in Kazakhstan and the number of installations covered does not allow for a statistical utilization of the emission factors obtained.

Offshore operations: There is very limited offshore activity in Kazakhstan and emissions from offshore facilities are not included in this analysis.

Giant fields: While extensive field information was made available for this study, covering a large share of the country's infrastructure, only limited data were available for Tengiz and Karachaganak, the two giant fields in Kazakhstan. The estimates associated with these two fields remain uncertain.

[4] The approach has been tested on eight distributions of EFs from measurements in the US and Canada.
[5] And are not included in the national estimates.

Current versus future abatement potential: The emissions and abatement potential were presented for 2015. Given the current uncertainty regarding future oil and gas markets, emission levels in the future were not projected.

Distribution: Finally, the analysis covers emissions upstream and midstream but distribution emissions are not included in the analysis.

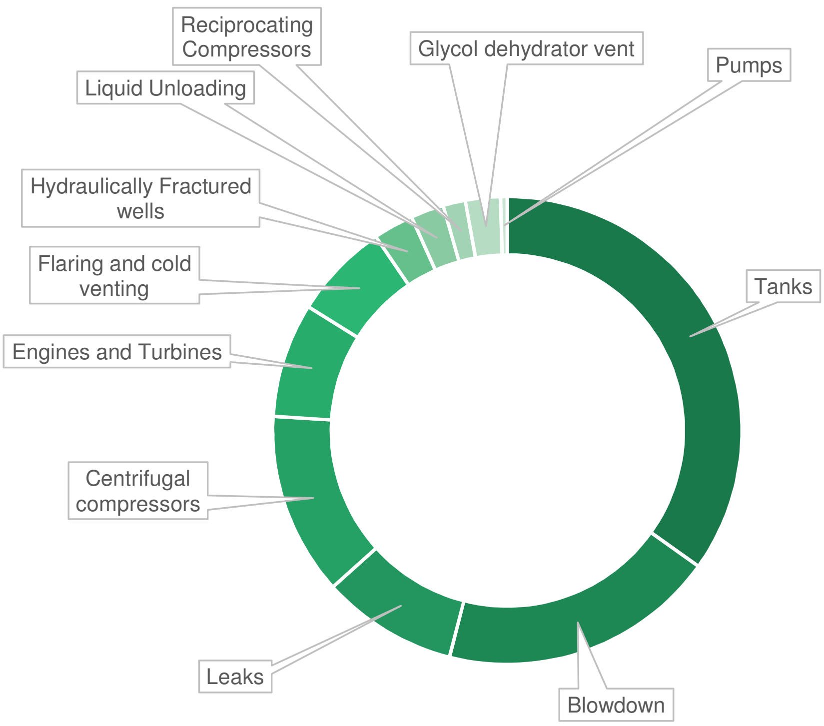
4. Results

4.1 Emissions estimates

The methane emissions in the upstream and midstream sectors in Kazakhstan account for 6.6 million tons of CO_2 equivalent ($MtCO_2e$)[6] or about 12.7 billion cubic feet of methane per year. Vents (i.e. engineered emissions) represent by far the majority of the emissions (90%).

The following figure presents the emissions per source category:

Figure 7: Emissions per emission source category



Key conclusions from the analysis are:

- Storage tanks are by far the largest source of methane emissions in the country's oil and gas sector. This can be explained by the large emission rates for individual storage tanks, as evidenced by the measurement campaigns, which is a result of very low penetration of the vapor recovery technology in the country.
- Blowdown and venting, in particular from gas compressor stations and from repair on the transmission network represents the second largest source of emission
- Leaks, in particular from the antiquated facilities (sometimes dating back to more than half a century ago), is the third largest source of methane emissions.
- Centrifugal compressors are the fourth largest source of emissions. The country has a large transmission network, which requires a large number of compressors to maintain the pressure

[6] Using GWP of 28 based on IPCC 5th Assessment Report.

inside it. Many upstream and midstream compressor stations in Kazakhstan are equipped with wet seal compressors venting methane from seal oil without any recovery of the vented gas.
- Contrary to the US and Canada, controllers do not represent a large share of the emissions. Based on field visits, interviews and responses to questionnaires, there are only a handful of gas-driven controllers in the country.

Comparison with the current Kazakh inventory
The official GHG inventories of Kazakhstan estimate fugitives methane emissions from oil and gas systems (Emission category 1.B.2.) as 3.2 million tCO_2e (with GWP of 21) in 2012[7] (Source 33). The estimate from our study is about 1.6 times the official Kazakhtan's GHG inventory estimates for these sources. A number of key hypotheses for the basis of the difference can be highlighted:
- **Gas flaring**: Based on Carbon Limits estimation, the official CH_4 emissions inventory from gas flaring in Kazakhstan assume an average combustion efficiency of 99.85%, which is much higher than the combustion efficiency used in our study (97% to 99%).
- **Liquid storage tanks**: Our study has revealed that tanks represent a major source of emissions, which is likely not fully reflected in the current national inventory[8].
- **Leaks**: Finally, leaks and fugitive emissions upstream and midstream could represent a large share of the balance between the two inventories.

4.2 Abatement potential and abatement costs estimates

Overall, the analysis shows that **at least**[9] 6.7 Bcf of methane or 3.5 million tCO_2e can be abated with existing technologies. About 50% of this potential has a negative abatement cost, i.e. it can be implemented with a positive net present value for the operating companies. Another 2.5 Bcf of methane or 1.3 million tCO_2e can be reduced with an abatement cost lower than 10 USD/tCO_2e.

The following figure presents the abatement potential depending on the abatement cost range and the emission category. Installation of vapor recovery units on tanks offers the largest potential with negative abatement costs. Recovery of methane from wet seal compressors accounts for about 1 Bcfof methane emission reductions, also achievable at negative abatement costs. Repairs of leaks and recovery of blowdown methane are the other largest source of emissions reduction potential with negative abatement costs.

On the other side of the spectrum, a number of emissions sources have limited abatement potentials, or abatement costs are relatively high. For example, recovery of upstream blowdown events, reduction of emissions from dehydrator vents and liquid unloading events are all sources with a high share of emission reduction opportunities that can only be achieved at costs exceeding 10 USD/tCO_2e.

[7] Excluding distribution
[8] The current inventory uses sub-sector wide emission factors
[9] Some technologies have not been considered and could represent additional abatement potential, such as recovery and flaring of cold vent points.

Figure 8: Abatement potential in Kazakhstan depending on the abatement cost range

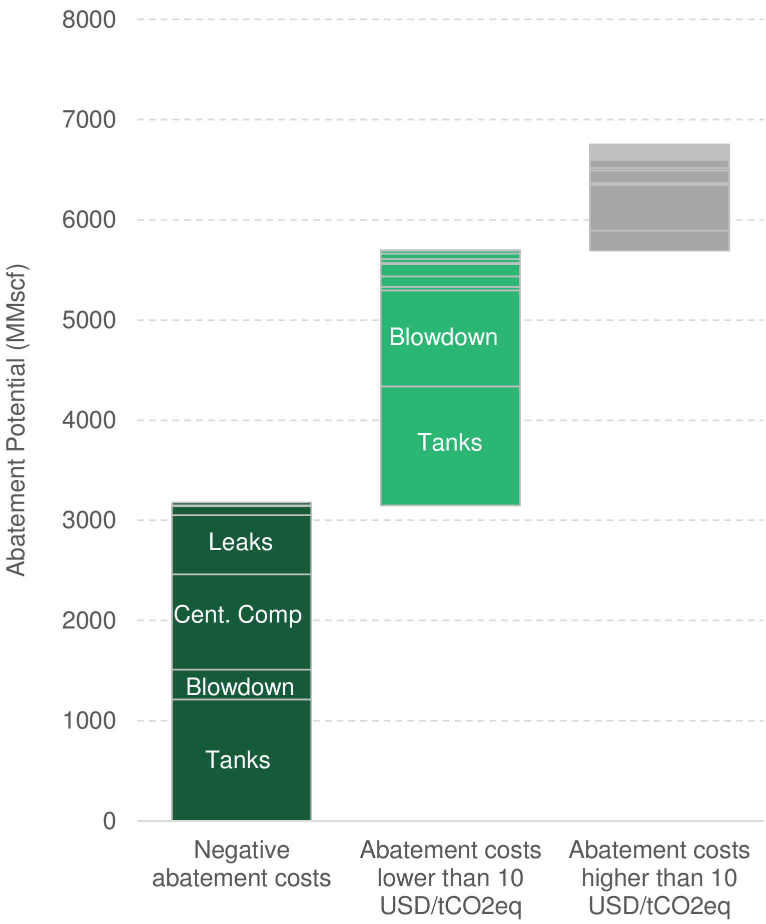


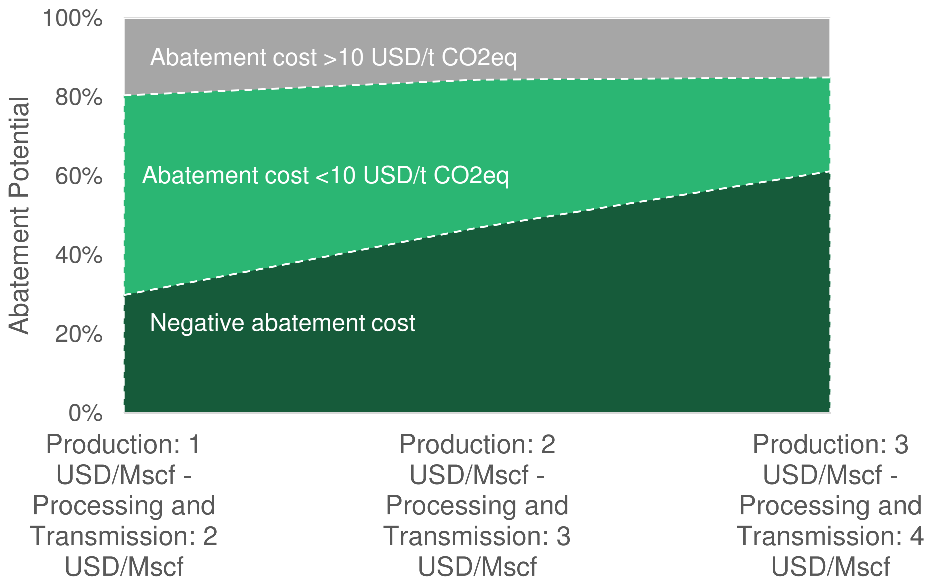
Table 2: Abatement potential in Kazakhstan depending on the abatement cost range (MMcf)

	Negative abatement costs	Abatement costs lower than 10 USD/tCO_2e	Abatement costs higher than 10 USD/tCO_2e
Tanks	1214	1185	202
Blowdown	296	961	456
Centrifugal compressors	953	33	0
Leaks	591	106	21
Hydraulically Fractured wells	0	122	122
Engines and Turbines	89	14	27
Liquid Unloading	0	35	82
Glycol dehydrator vent	0	58	114
Reciprocating Compressors	9	26	34
Pumps	27	5	0

4.3 Sensitivity to gas price

Generally, abatement costs are sensitive to the gas price as part of the abatement cost is assumed to be recouped through the sale of natural gas saved by the use of emission reduction technologies.

Figure 9 Distribution of abatement costs depending on the gas price assumption



The share of the abatement potential with negative abatement cost (i.e. where the savings from the gas recovered exceeds the project's implementation costs) naturally increases as gas prices increase, see Figure 9. With a gas price of 1 USD/Mscf for production facilities and 2 USD/Mscf for processing and transmission facilities, only 30% of the abatement is economic to implement without complementary support mechanisms. This share increases to almost 50% by increasing the gas price by 1 USD/Mscf. The share of the abatement potential with high abatement cost (>10 USD/Mscf) remains fairly stable around 20% for all the gas prices considered.

4.4 Concluding remarks

This analysis is an integral part of the larger methane program in Kazakhstan, which aims at creating awareness on methane emissions from oil and gas systems and at triggering sustainable emission reductions throughout the country. The work performed can be leveraged both by the oil and gas industry in Kazakhstan and by the Kazakh authorities to identify emission reduction opportunities.

The analysis also illustrated possible approaches and methodologies to estimate methane emissions in an oil and gas producing country using both on-site measurement data and detailed information on equipment counts and technologies applied. The results show that methane emission profile is country-specific and depends heavily on the local practice.

5. Annex 1: Tables of assumptions

Category	Category	Activity Factor	Activity factor - Unit	Activity factor - Source	Applicability of the abatemen	Applicability of the abatement - source	Abatement efficier	Abatement efficiency - source
CAT_1	Flaring-Production	26045	MMscf	Source 8				
CAT_3	Cold-Venting	69	MMscf	Source 2 and 7				
CAT_4	Leaks_Production	747498519	boe/year	Source 22	100%	Source 7	60%	Source 3
CAT_6	Leaks_Processing	459030	MMscf of gas processed	Source 22, 33 and 7	100%	Source 7	60%	Source 3
CAT_8	Leaks_Compressor Stations	84	# of equipment	Source 13	100%	Source 7	60%	Source 3
CAT_9	Liquid storage tanks - non mitigated	1313	# of tanks	Source 1	80%	Source 7	75%	Source 25
CAT_10	Liquid storage tanks with VRU	146	# of tanks	Source 1				
CAT_11	Centrifugal Compressors with wet seal - upstream	12	# of compressors	Source 1	70%	Source 7	95%	Source 3
CAT_12	Centrifugal Compressors with wet seal - Transmission an	235	# of compressors	Source 1	70%	Source 7	95%	Source 3
CAT_13	Centrifugal Compressors with dry seal	87	# of compressors	Source 1				
CAT_14	Small Gas Engines and Turbine	20937	MMscf of methane	Source 7, 16 and 19	70%	Source 7	21%	Source 4
CAT_15	Reciprocating Compressors upstream	350	# of compressors	Source 1	100%	Source 7	35%	Source 3
CAT_16	Reciprocating Compressors Refineries	57	# of compressors	Source 1	100%	Source 7	35%	Source 3
CAT_17	Reciprocating Compressors Transmissions	19	# of compressors	Source 1	100%	Source 7	35%	Source 3
CAT_18	Liquid_Unloading	4950	# of event/year	Source 1 and 12	50%	Source 7	80%	Source 4
CAT_19	Hydraulically Fractured wells mitigated	401	# of event per year	Source 1 and 7	80%	Source 7	90%	Source 4
CAT_20	Hydraulically Fractured wells non mitigated	172	# of event per year	Source 1 and 7				
CAT_21	Dehydrator Vent Processing non mitigated	367224	MMcf of throughput	Source 22, 33 and 7	90%	Source 7	67%	Source 4
CAT_22	Dehydrator Vent Processing mitigated	91806	MMcf of throughput	Source 22, 33 and 7				
CAT_23	Dehydrator Vent transmission non mitigated	2220293	MMcf of throughput	Source 13 and 7	90%	Source 7	67%	Source 4
CAT_24	Dehydrator Vent transmission mitigated	555073	MMcf of throughput	Source 13 and 7				
CAT_25	Natural Gas Driven Chemical Injection Pumps	35	# of pumps	Source 1 and 7	80%	Source 3, source 7	100%	Source 3
CAT_26	KimrayPumps (Glycol)	45903	MMcf of throughput/year	Source 22	50%	Source 3, source 7	100%	Source 3
CAT_27	Blowdown_vessels_nonmitigated	4532	#	Source 1 and 7	70%	Source 7	91%	Source 26 and 4
CAT_28	Blowdown_PRV_nonmitigated	9064	#	Source 1 and 7	70%	Source 7	91%	Source 26 and 4
CAT_29	Blowdown_routine_compressor_nonmitigated	1203	#	Source 1 and 7	50%	Source 7	98%	Source 26 and 4
CAT_30	Blowdown_start_compressor_nonmitigated	1203	#	Source 1 and 7	50%	Source 7	98%	Source 26 and 4
CAT_32	Blowdown_GPP_nonmitigated	16	#	Source 14, 15	90%	Source 4 and 7	50%	Source 26 and 4
CAT_33	Blowdown_compressor_station_nonmitigated	56	#	Source 13	70%	Source 3	95%	Source 3
CAT_34	Blowdown_natural_gas_trunklines_nonmitigated	11229	km	Source 13, Source 7	90%	Source 25	85%	Source 25
CAT_35	Blowdown_natural_gas_trunklines_mitigated	4813	km	Source 13, Source 7				
CAT_36	Large Gas Engines and Turbine non mitigated	66999	MMscf of methane	Source 7, 16 and 19	70%	Source 7	21%	Source 4
CAT_37	Large Gas Engines and Turbine mitigated	16750	MMscf of methane	Source 7, 16 and 19				

Category_	Category	Central Emission factor	Low Emission factor	High Emission factor	Emission factor -Unit	Emission factor - sou
CAT_1	Flaring-Production	2%	1%	5%	%	Source 9
CAT_3	Cold-Venting	100%	100%	100%	%	NA
CAT_4	Leaks_Production	0.350	0.020	1.400	scf/boe	Source 2 and 10
CAT_6	Leaks_Processing	0.190%	0.076%	0.380%	% of the Throughput	Source 2, 29 and 10
CAT_8	Leaks_Compressor Stations	0.76	0.25	8.31	MMscf/equipment/year	Source 2 and 10
CAT_9	Liquid storage tanks - non mitigated	3.30	1.00	7.00	MMscf/tank/year	Source 2 and 10
CAT_10	Liquid storage tanks w ith VRU	0.83	0.25	1.75	MMscf/tank/year	Source 2 and 10
CAT_11	Centrifugal Compressors w ith w et seal - upstream	6.00	4.00	17.58	MMscf/compressor/year	Source 23, 2 and 17
CAT_12	Centrifugal Compressors w ith w et seal - Transmission an	6.00	4.00	17.58	MMscf/compressor/year	Source 23, 2 and 17
CAT_13	Centrifugal Compressors w ith dry seal	1.50	0.90	3.00	MMscf/compressor/year	Source 23 and 17
CAT_14	Small Gas Engines and Turbine	1.0%	0.5%	2.0%	%	Source 18 and 28
CAT_15	Reciprocating Compressors upstream	0.42	0.09	1.93	MMscf/year	Source 2, 10 and 23
CAT_16	Reciprocating Compressors Refineries	0.64	0.16	5.91	MMscf/year	Source 2, 10 and 23
CAT_17	Reciprocating Compressors Transmissions	0.74	0.11	5.00	MMscf/year	Source 2, 10 and 23
CAT_18	Liquid_Unloading	0.06	0.02	0.11	MMscf/event	Source 12
CAT_19	Hydraulically Fractured w ells non mitigated	0.85	0.41	10.77	MMscf/event	Source 20 and 21
CAT_20	Hydraulically Fractured w ells mitigated	0.08	0.04	1.08	MMscf/event	Source 20 and 21
CAT_21	Dehydrator Vent Processing non mitigated	0.00021	0.00007	0.00044	MMscf/MMScf throughput	Source 23 and 10
CAT_22	Dehydrator Vent Processing mitigated	0.00007	0.00002	0.00014	MMscf/MMScf throughput	Source 23 and 10
CAT_23	Dehydrator Vent transmission non mitigated	0.00009	0.00003	0.00020	MMscf/MMScf throughput	Source 23 and 10
CAT_24	Dehydrator Vent transmission mitigated	0.00003	0.00001	0.00007	MMscf/MMScf throughput	Source 23 and 10
CAT_25	Natural Gas Driven Chemical Injection Pumps	0.29	0.11	0.67	MMcf/year	Source 10, 27
CAT_26	KimrayPumps (Glycol)	0.00106	0.00034	0.00228	MMcf/MMScf	Source 23, 27
CAT_27	Blow dow n_vessels_nonmitigated	0.00	0.00	0.00	MMscf/Equipment count	Source 24
CAT_28	Blow dow n_PRV_nonmitigated	0.00	0.00	0.00	MMscf/Equipment count	Source 24
CAT_29	Blow dow n_routine_compressor_nonmitigated	0.00	0.00	0.01	MMscf/Equipment count	Source 24
CAT_30	Blow dow n_start_compressor_nonmitigated	0.01	0.01	0.01	MMscf/Equipment count	Source 24
CAT_32	Blow dow n_GPP_nonmitigated	4.06	1.55	10.64	MMscf/GPP	Source 1 and 24
CAT_33	Blow dow n_compressor_station_nonmitigated	8.83	0.64	11.65	MMscf/Compressors stations	Source 1 and 24
CAT_34	Blow dow n_natural_gas_trunklines_nonmitigated	0.16	0.06	0.15	MMscf/km	Source 25
CAT_35	Blow dow n_natural_gas_trunklines_mitigated	0.02	0.01	0.02	MMscf/km	Source 25
CAT_36	Large Gas Engines and Turbine non mitigated	1.0%	0.5%	2.0%	%	Source 18 and 28
CAT_37	Large Gas Engines and Turbine mitigated	0.8%	0.4%	1.6%	%	Source 18 and 28

Category_ID	Category	Mitigation description	CAPEX average (USD)	CAPEX low (USD)	CAPEX high (USD)	OPEX (USD)	Source
CAT_4	Leaks_Production	LDAR	0	0	0	667	Source 25
CAT_6	Leaks_Processing	LDAR	0	0	0	5,000	Source 25
CAT_8	Leaks_Compressor Stations	LDAR	0	0	0	2,000	Source 25
CAT_9	Liquid storage tanks - non mitigated	Install VRU	50,000	20,000	100,000	2,250	Source 25, 3 and 4
CAT_11	Centrifugal Compressors with wet seal - upstream	Recovery system	50,000	20,000	100,000	1,500	Source 3 and 25
CAT_12	Centrifugal Compressors with wet seal - Transmission and refineries	Recovery system	50,000	20,000	100,000	1,500	Source 3 and 25
CAT_14	Small Gas Engines and Turbine	Install automated air/fuel ratio controls	138,000	98,000	161,000	0	Source 26
CAT_15	Reciprocating Compressors upstream	Early replacement of rod packing systems	6,000	6,000	7,800	0	Source 3, 4, 5, and 25
CAT_16	Reciprocating Compressors Refineries	Early replacement of rod packing systems	6,000	6,000	7,800	0	Source 3, 4, 5, and 25
CAT_17	Reciprocating Compressors Transmissions	Early replacement of rod packing systems	6,000	6,000	7,800	0	Source 3, 4, 5, and 25
CAT_18	Liquid_Unloading	Install plunger lift	20,000	5,646	28,400		Source 3, 4 and 5
CAT_19	Hydraulically Fractured wells mitigated	Reduced emissions completion	0			30,038	Source 4 and 26
CAT_21	Dehydrator Vent Processing non mitigated	Optimize glycol circulation rate and install flash tank separators	9,500	6,540	20,000	50	Source 4 and 26
CAT_23	Dehydrator Vent transmission non mitigated	Optimize glycol circulation rate and install flash tank separators	9,500	6,540	20,000	50	Source 4 and 26
CAT_25	Natural Gas Driven Chemical Injection Pumps	Replace chemical injection pumps with solar electric pumps	5,000	4,000	6,000	75	Source 3
CAT_26	KimrayPumps (Glycol)	Replace Kimray pumps with electric pumps	10,000	5,000	15,000	2,000	Source 3 and 4
CAT_27	Blowdown_vessels_nonmitigated	Connecting blowdown vent lines to the fuel gas system and recoveri	2,000	2,000	2,000	0	Source 26
CAT_28	Blowdown_PRV_nonmitigated	Connecting blowdown vent lines to the fuel gas system and recoveri	2,000	2,000	2,000	0	Source 26
CAT_29	Blowdown_routine_compressor_nonmitigated	Installing ejectors on compressor blowdown vent lines.	11,644	11,644	11,644	0	Source 26
CAT_30	Blowdown_start_compressor_nonmitigated	Installing ejectors on compressor blowdown vent lines.	11,644	11,644	11,644	0	Source 26
CAT_32	Blowdown_GPP_nonmitigated	Installing surge vessels for capturing blowdown vents	936,150	650,970	936,150	34,987	Source 4
CAT_33	Blowdown_compressor_station_nonmitigated	Redesign Blowdown Systems and ESD	20,000	15,000	75,000	0	Source 3, 7
CAT_34	Blowdown_natural_gas_trunklines_nonmitigated	Pipeline Venting - Pump-Down Before Maintenance - KZ	5,000	4,000	6,000	42	Source 25
CAT_36	Large Gas Engines and Turbine non mitigated	Install automated air/fuel ratio controls	138,000	98,000	161,000	0	Source 26

6. Annex 2: References

Source 1	Compiled answers to the questionnaire on activity factors and current practices in Kazakhstan, Carbon Limits, 2016.
Source 2	Results of the measurement campaigns performed in Kazakhstan, Carbon Limits, 2015.
Source 3	Economic Analysis of Methane Emission Reduction Opportunities in the U.S. Onshore Oil and Natural Gas, ICF, 2014. https://www.edf.org/sites/default/files/methane_cost_curve_report.pdf
Source 4	Global Mitigation of Non-CO2 Greenhouse Gases, 2010-2030, EPA, 2014. http://www3.epa.gov/climatechange/EPAactivities/economics/nonco2mitigation/execsumm/index.html
Source 5	Waste Not: Common sense ways to reduce methane pollution from the oil and natural gas industry, CATF, 2014. http://www.catf.us/resources/publications/view/206
Source 6	Information from technology providers – Personal communication
Source 7	Author assumptions based on interviews with Oil and Gas experts in Kazakhstan and field experience
Source 8	Plan for the development of the gas sector in The Republic of Kazakhstan until 2030, Ministry of Energy of Kazakhstan, 2014 http://energo.gov.kz/assets/old/uploads/files/2015/1275-rus.doc
Source 9	Parameters for Properly Designed and Operated Flares, EPA, 2012, http://www3.epa.gov/airtoxics/flare/2012flaretechreport.pdf
Source 10	Quantifying Cost-effectiveness of Systematic Leak Detection and Repair Program Using Infrared Cameras, Carbon Limits, 2014 (and the associated database) http://www.catf.us/resources/publications/view/198
Source 12	Oil and Natural Gas Sector Liquids Unloading Processes, EPA; 2014 http://www3.epa.gov/airquality/oilandgas/pdfs/20140415liquids.pdf
Source 13	KazTransGas public website, 2015, http://www.kaztransgas.kz/index.php/en/main-page/general-information
Source 14	IHS data for Kazakhstan, 2011.
Source 16	Kazakh operator's website and annual reports, 2014 and 2015
Source 17	Oil and Natural Gas Sector Compressors, EPA, 2014. http://www3.epa.gov/airquality/oilandgas/2014papers/20140415compressors.pdf
Source 18	CATALYTIC EMISSION CONTROL WITH RESPECT TO CH4 AND CO FOR HIGHLY EFFICIENT GAS FUELED DECENTRALISED HEAT AND POWER PRODUCTION. Jan de Wit, Keld Johansen, Poul L. Hansen, Helle Rossen, Niels B. Rasmusse. http://www.dgc.eu/sites/default/files/filarkiv/documents/C0001_catalytic_emission_control.pdf
Source 20	Co-Producing Wells as a major source of Methane Emissions: A review of recent analyses, EDF, 2014. http://blogs.edf.org/energyexchange/files/2014/03/EDF-Co-producing-Wells-Whitepaper.pdf
Source 21	Oil and Natural Gas Sector Hydraulically Fractured Oil Well Completions and Associated Gas during Ongoing Production, EPA, 2014. http://www3.epa.gov/airquality/oilandgas/2014papers/20140415completions.pdf
Source 22	Statistical Review of World Energy, BP, 2015. http://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html
Source 23	Annexes to the Inventory of U.S. GHG Emissions and Sinks, EPA, 2015. http://www3.epa.gov/climatechange/Downloads/ghgemissions/US-GHG-Inventory-2014-Annexes.pdf
Source 24	Methane emissions from the Natural Gas Industry, GRI, 1996.
Source 25	Techno economic analysis of pilot projects in Kazakhstan, Carbon Limits, 2015 and 2016.
Source 26	Recommended Technologies and Practices, Natural gas star program. http://www3.epa.gov/gasstar/tools/recommended.html
Source 27	Final Report For Determining Bleed Rates for Pneumatic Devices in British Columbia, Prasino, 2013. http://www2.gov.bc.ca/assets/gov/environment/climate-change/stakeholder-support/reporting-regulation/pneumatic-devices/prasino_pneumatic_ghg_ef_final_report.pdf
Source 28	Methane and Formaldehyde Emissions of Gas Engines, CIMAC, 2014. http://www.cimac.com/cms/upload/workinggroups/WG17/CIMAC_Position_Paper_WG17_Methane_and_Formaldehyde_Emissions_2014_04.pdf
Source 29	Cost effective Directed Inspection and Maintenance control opportunities at Five gas processing plants and upstream gathering compressor stations and well sites. Clearstone 2006.

Source 30	Global anthropogenic methane emissions 2005–2030: technical mitigation potentials and costs. IIASA, 2012 http://www.atmos-chem-phys.net/12/9079/2012/acp-12-9079-2012.pdf
Source 31	Untapped Potential: Reducing Global Methane Emissions from Oil and Natural Gas Systems, Rhodium, 2015 http://rhg.com/reports/untapped-potential
Source 32	International energy data and analysis- Kazakhstan. EIA, 2015 https://www.eia.gov/beta/international/analysis_includes/countries_long/Kazakhstan/kazakhstan.pdf
Source 33	Greenhouse Gas Inventory Data - Detailed data by Party http://unfccc.int/di/DetailedByParty/Event.do?event=go NIR: http://unfccc.int/national_reports/annex_i_ghg_inventories/national_inventories_submissions/items/8812.php